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Geological Investigations of the Pennsylvania Piedmont

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DEPARTMENT OF INTERNAL AFFAIRS
Genevieve Blatt, Secretary

BUREAU OF
TOPOGRAPHIC AND GEOLOGIC SURVEY
Arthur A. Socolow, State Geologist

J. FREEDMAN
D. U. WISE } *Franklin and Marshall College, Lancaster, Pa.*
R. D. BENTLEY *Georgia Geological Survey, Atlanta, Ga.*

Pattern of Folded Folds in the Appalachian Piedmont Along Susquehanna River

Abstract: Structural details are presented for 22 key stations along a 30-mile cross section of the Pennsylvania Piedmont along the Susquehanna River. Three major cleavages, S_1, S_2, S_3, with associated folds F_1, F_2, F_3, vary systematically and independently in orientation across the region. The pattern seems to have developed by successive superposition of three deformations, D_1, D_2, and D_3, each involving a characteristic style of yield.

The oldest deformation, D_1, utilized mechanisms of flowage and isoclinal folding to create the dominant schistosity of the region. In the southeast the F_1 axial planes and the associated S_1 dip steeply to the southeast but flatten northwestward to become part of a recumbent fold system suggestive of northwestward tectonic transport from a root zone in the southeast.

The D_2 deformation has uniform orientations across the region and is characterized by slip folding along S_2. As the largest F_2 structure, the Tucquan anticline involves folding of basement in the Mine Ridge area.

Evidence of D_3 appears only in the extreme northwest and southeast of the Susquehanna section. The extreme southeast is characterized by intense F_3 slip folds with northwest-dipping axial planes becoming steeper to the northwest. In the extreme northwest D_3 is marked by nearly vertical S_3 fracture cleavage planes.

With changing lithology the deformation planes vary in development and style but not in local orientation. All deformations cross the classic Martic Line without change, indicating that this contact predates all major folding. The over-all style of deformation seems to change with time from predominant flow to predominant fracture, and from nappelike flowage of sedimentary rocks to basement involvement.

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Geological Society of America Bulletin, v. 75, p. 621–638, 6 figs., 5 pls., July 1964

INTRODUCTION

Multiple folding is common in many mountain ranges. In the Appalachian Piedmont of Pennsylvania folded folds have been noted by Knopf and Jonas (1929), Jonas (1937), Cloos and Hietanen (1941), and McKinstry (1961), among others, but none of these workers has attempted to trace the different fold systems across the region.

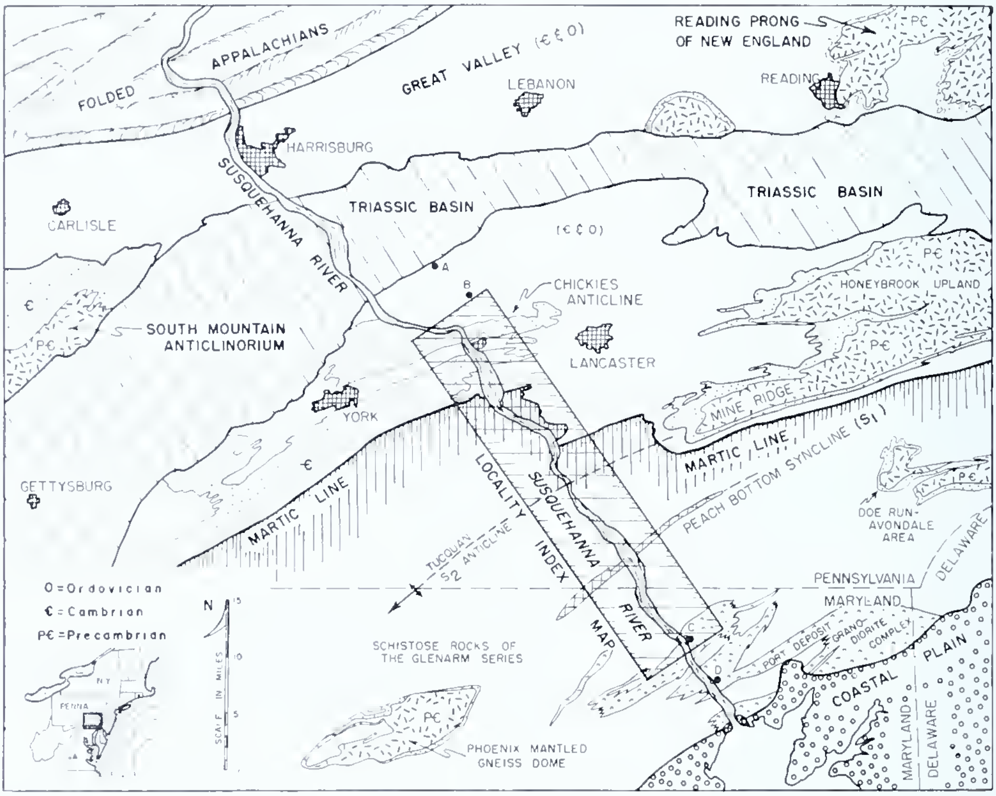

Figure 1. Index map

Multiple fold systems are formed by either a very complex stress system operating at a single time or by superposition of several stress systems operating at different times. The three major fold patterns of this part of the Appalachian Piedmont seem to represent successive superposition of deformation; this is evidenced by the systematic but independent orientations of the different systems, systematic age sequences of fold elements at most outcrops, and characteristic style of deformation and metamorphism associated with each of the systems.

This paper describes the variation in fold patterns across several tectonic zones of the Appalachian Piedmont along Susquehanna River. The area extends from the edge of the mantled gneiss dome region of Maryland (Fig 1) northwestward through a belt of schistos rock of the Glenarm Series, across the Marti Line and into the Outer Piedmont zone of les metamorphosed Cambrian and Ordovicia limestones and quartzites in Pennsylvania. Th age and nature of the contact of the Glenar Series with the Cambrian and Ordovician limestones is the heart of the Martic problem which is described by Cloos and Hietane (1941). The relationship of this contact to suc local structures as the Peach Bottom synclin and Tucquan anticline (Figs. 1, 2) are part o the problem.

This area was chosen for its 30 miles of nearl continuous river exposure and railroad cuts Photographs of the changing fold character i these cuts are arranged from south to north i Plates 2–5. All photographs were taken lookin northeastward and may be compared directl with Figure 6. Precise locations are denoted b the pole numbers of the railway electrificatio ranging consecutively from 300 in the sout near Conowingo, Maryland, to 1200 in th north near Washington Boro, Pennsylvania.

Many workers (Knopf and Jonas, 1929

tose and Jonas, 1939; Hietanen, 1951) have ndicated the complex metamorphic and de- ormational history of this area. Dating of rocks adjacent areas of the Piedmont (Wasserburg nd others, 1957) also indicates a complex istory involving at least two phases of meta- orphism. Knopf and Jonas (1929) found ineralogic evidence for two periods of metamorphism: a high-grade earlier period masked by later retrograde metamorphism. Preliminary work by two of the present writers supports a similar multiple history of metamorphism. A correlation of *S*-surfaces with phases of metamorphism awaits further knowledge of age dating and a study of micas associated with the various *S*-surfaces. These studies are in progress.

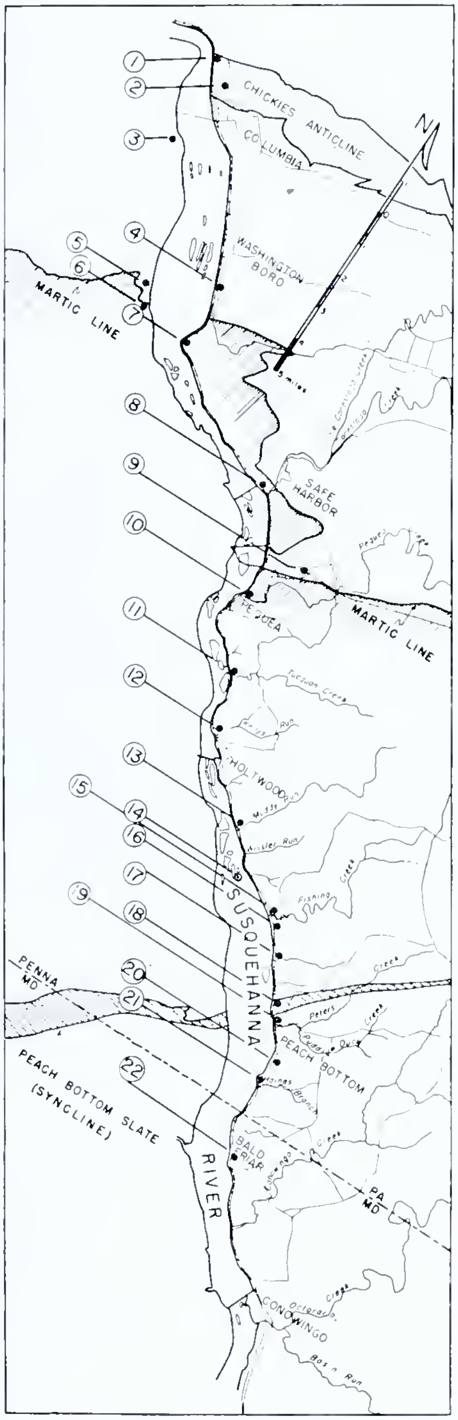

Figure 2. Locality index map

The rocks vary in lithology, competence, and metamorphic rank along the line of stations. The over-all metamorphic intensity decreases from south to north (Knopf and Jonas, 1929), although this variation is not apparent within smaller areas. Detailed structure stations 22–19 and 17–15 (Fig. 2) are in the Peters Creek Schist, composed of competent chloritic quartzites intercalated with less competent chlorite-quartz schists. Stations 15–10 and 8–6 are in the Wissahickon Schist, a series of intricately interbedded, incompetent, chlorite-albite schists, quartz-muscovite schists, and calcareous quartzites. All of these are part of the probable lower Paleozoic Glenarm Series. To the north, along the Martic Line, these formations rest on the Ordovician Conestoga Limestone at a contact of debatable origin (Cloos and Hietanen, 1941). The Conestoga Limestone at Stations 4, 5, and 9 is an incompetent, impure marble with local arenaceous marbles and very incompetent phyllites. Stations 2 and 3 are in the competent, Cambrian Antietam quartz-muscovite-biotite schist. The northernmost station (1) is in the Cambrian Chickies Quartzite, a very competent orthoquartzite with sparse, thin interbeds of chlorite-quartz phyllite.

The metamorphic history of these rocks is closely interwoven with the structural history of the region. The authors hope that the present separation of the multiple deformations will provide a technique with which to study the polygenetic metamorphic and structural history from Coastal Plain through Folded Appalachians.

ACKNOWLEDGMENTS

We are grateful to the many people and organizations who contributed to this study. A National Science Foundation grant made to Franklin and Marshall College provided the funds. Ernst Cloos stimulated and encouraged the investigation and lent maps, rocks, and thin sections. Other staff members and former graduate students from The Johns Hopkins University, F. J. Pettijohn, C. Hopson, O.

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TERMINOLOGY

A major difficulty in working with multiple fold systems is semantics. Simultaneous consideration must be given to planes, lines, and stresses of several kinds and ages that vary dependently or independently in time and space. The problem is analogous to that of higher mathematics where a shorthand notation is necessary to simplify a complicated terminology sufficiently to permit one to see the underlying principles.

The "shorthand" terminology of letters used throughout this paper follows the general practice of Sander (1930), Fairbairn (1949), and Turner and Verhoogen (1960):

S is any surface or plane of inhomogeneity.
L stands for any linear feature in the rock.
F represents a fold defined by any deformed *S*-surface.
A is a fold axis defined by any deformed *S*-surface.
D is a period or time of deformation.

Numerals suffixed to these letters indicate the number in the sequence of deformation periods from oldest to youngest responsible for their origin. A significant change is the use of S_0 rather than S_1 for original stratification or bedding. This modification simplifies the shorthand by maintaining the same number for all *S*-surfaces, lineations, folds, and fold axes associated with a given deformation number (*e.g.*, S_2, F_2, and A_2 were created in D_2 time).

In the Susquehanna region, *S*-surface numbers range from 0 to 4, to create the potential for 10 different types of lineation by intersections of the five planes. No more than five of the ten potential intersections were found at any outcrop because of differing degrees of development of *S*-surfaces. These intersection lineations are indicated by the subscript numbers of the *S* planes producing them. For example, $L_{1\times3}$ (read: L one cross three) is forme by the line of intersection of S_1 and S_3. Sinc *S*-surface numbers are the same as the deformation numbers, it follows that the $L_{1\times}$ was formed in D_3 time.

A similar system is necessary to distinguis some of the folds. For instance, if S_0 and S are not parallel, a later deformation, D_2, wi create two kinds of F_2 folds with differin orientations. The fold defined by bedding, S will have one orientation of axis, whereas tha defined by an S_1 cleavage will have a differen axis within the same axial plane. To distinguis them, two subscripts are necessary: the first the plane that is folded, and the second is th number of the superimposed deformation an *S*-surface. The fold created by D_2 and define by bedding (S_0) would be $F_{0\times2}$ (*F* zero cro two) whereas the folded cleavage would b $F_{1\times2}$. The fold axes would be $A_{0\times2}$ and $A_{1\times}$ Throughout this paper the zero (for S_0 bedding) is implied but omitted unless necessar for clarity because most folds are defined b bedding. (The F_3 is a fold in bedding that wa created in D_3 time and has an A_3 axis).

Age connotations have become associate with anticline and syncline. Indiscriminate us of these terms in areas of multiple deformatio can result in major confusion, particularly recumbent folds are present. The terms ant form and synform are used for structures havin an anticlinal or synclinal shape respectively bu showing age relationships that may differ fro the ordinary. For instance an anticline that ha been overturned to have the form of a synclin will be termed a synformal anticline. Whe unambiguous the terms anticline and synclin are used.

Terminology and structural shorthand not tions used throughout this paper are based o the system just described. In referring to th work of others in this area, we have transpose their notation into this system to avoid co fusion.

PREVIOUS WORK

Jonas and Stose did the basic mapping of th region in the 1920's and 1930's. They mappe Lancaster quadrangle (1930), Middletow quadrangle (1933), and York County (1939 Knopf and Jonas (1929) were the first to ma the area near the Martic Line (McCalls Ferr Quarryville quadrangles). This work starte a controversy that resulted in a number papers on age and structure of the rocks b Miller (1935), Mackin (1935), Bailey an

Iackin (1937), and Swartz (1948); however, he only detailed work in the area was done by loos and Hietanen (1941). This work sumarized the problem and by petrofabrics and tructural field analysis established that all $_1$ and S_2 structures transgressed the Martic ine without any change. Cloos and Hietanen oncluded that the repetition of the geologic

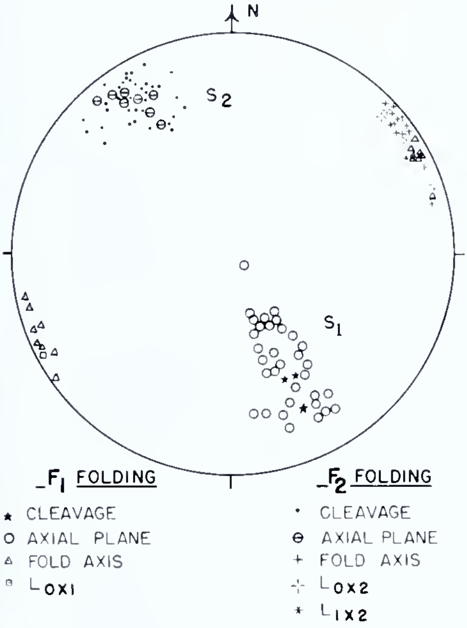


Figure 3. Equal-area plot: multiple folding in Colemanville railroad cut

ction north of the Martic Line predated the eformation (D_1 and D_2) and metamorphism. nas (1937) correctly summarized the strucure of the Tucquan anticline by recognizing nd separating the recumbent folds (F_1) from steeper S_2 cleavage. Cloos and Hershey (1936) lled attention to the constancy of the fracture leavage (S_2). Hershey (1937) mapped the uthern end of the Susquehanna River section hile studying the Port Deposit Granodiorite omplex and Agron (1950) recognized multiple lding while studying the Peach Bottom Slate elt. Wise (1953) studied the stratigraphy and ructure of the Conestoga Limestone. More ecently, McKinstry (1961) interpreted strucural features as folded folds in adjacent hester County.

ECHNIQUES AND VALIDITY F METHODS

The methods used in this study are a variaon of the standard techniques of joint and etrofabric studies where lineations and poles planes are plotted on the lower hemisphere of an equal-area net. Each plot represents a set of measurements in a restricted outcrop area or station. The method involves: plotting all data in the field; dividing the structural elements into as many classes as possible, including age relationships on the basis of field characteristics; and maintaining these distinctions on the field plots by color and code symbol. The relative age relationships utilized were: offset of one group of *S*-surfaces by a younger group; folding or slip folding of one group of *S*-surfaces on a younger group of surfaces; visible deformation of lineations by refolding on younger axes or surfaces.

An independent check on the accuracy of these relative age criteria and determinations is the concurrent work of Lapham and McKague (1964) on multiple deformations associated with a serpentinite belt in the same area. They find evidence of the same deformational sequence in serpentinite bodies and in the surrounding schists.

Contouring plots with several classes of interspersed data is not practical unless separate plots are prepared for each. As this separation would increase the number of plots and obscure mutual relationships, most of the figures in this paper have only lines encircling the various classes of data points.

The measurement techniques can be described best by using the Colemanville railroad cut (Fig. 2, station 9) as a sample outcrop. The outcrop is Conestoga Limestone with well-defined bedding (S_0) contorted into a complex of *S*-surfaces and fold axial planes. Relative age indicators (Pl. 3, fig. 2) distinguish S_1 (schistosity) and many parallel F_1 isoclinal fold axial planes from younger S_2 slip cleavages with rarer F_2 slip folds.

As in most of the outcrops, two types of lineations appear in the Colemanville railroad cut (Fig. 3): fold axes (A_1, A_2) from several periods of deformation, and lines of intersection of the several *S*-surfaces ($L_{0\times1}$, $L_{1\times2}$, *etc.*). The A_1 axes, associated with F_1 isoclinal folds are essentially horizontal with only slight plunges to the northeast or southwest. The bedding-schistosity intersection ($L_{0\times1}$) is parallel to this axis. The A_2 axes plunge gently to the northeast parallel to their associated intersection lineations $L_{0\times2}$ and $L_{1\times2}$. The two types of potential A_2 axes, $A_{0\times2}$ and $A_{1\times2}$, are parallel here because the previous F_1 isoclinal folding caused parallelism of the S_0 and S_1 planes that define the axes.

The relative dependence or independence in orientation of fold axes and intersection lineations defines an important concept. Only fold axes and related lineations associated with the first deformation (D_1) are completely independent in orientation. Younger fold axes (A_2) and their associated lineations ($L_{0\times2}$, $L_{1\times2}$) are defined by the intersection of their S-surface (S_2) with the dominant planes (S_0–S_1). All fold axes in the lower Susquehanna region, other than A_1, can be derived from S-surfaces by calculating the line of intersection of the two surfaces. For example, in Figure 3, where the strike of S_1 and S_2 is not precisely the same, the line of intersection will have a slight plunge to the northeast, the same orientation as the lineations associated with the F_2 folds. At other stations where the the S-surfaces are more nearly parallel, minor variability in orientation causes a great variability of strike and plunge of younger linear structures. If the planes differ only in dip, the fold axes caused by their intersection will be horizontal, whereas slight differences in strike can cause the axes to plunge directly down the dip of the planes. This relationship can produce large areas of constantly plunging fold axes in rocks where older more obscured isoclinal folding determines a dominant plunge of rock units in some other direction. Many of the anomalous fold and plunge patterns of the nearby Lancaster Valley originate in this way.

STRUCTURAL STATIONS ALONG SUSQUEHANNA RIVER

General Statement

Structural details were measured at 22 stations along Susquehanna River. The stations are spaced at ½ to 2-mile intervals (Fig. 2). Outcrops at and between stations were examined carefully as part of a larger study of the petrology, metamorphism, and stratigraphy of the Glenarm rocks. It was thus possible to select stations of maximum exposure, favorable lithology, and excellent S-surface development.

The basic, unprocessed data are presented in the 22 plots of Plate 1, arranged sequentially from northwest to southeast. With the labels of the encircled clusters it is possible to trace the positions of an S-surface maximum across the region. For example, the S_2 maximum remains in essentially the same place on the plots, indicating a nearly constant orientation of S_2 planes. The S_1 maximum shifts progressively from stations 6 through 19 to merge with the S_2 maximum in stations 20 to 22. In the south S_1 is a dominant schistosity in the Glenarm Series. In the northernmost part of th area S_1 is present but hard to detect in th brittle quartzites.

S-surfaces younger than S_1 or S_2 are we developed in the northwest and southeast c the area (Pl. 1) but are obscure in the centra section. The younger S-surfaces in these tw separate areas have been designated S_{3N} (north and S_{3S} (south) because of uncertainty as t whether they represent precisely the sam deformation in both areas. For the most par S_{3N} is a steeply dipping fracture cleavag locally grading into a closely spaced join set. The S_{3S} consists of very well-develope slip planes and slip cleavages that vary system atically in orientation through an area of ex tremely prominent slip folding in the south.

Summary diagrams of all S-surface orienta tions are presented in Figure 4. All the pol of a given S-surface on Plate 1 have been use in Figure 4. The S_1 poles form an exceller girdle indicative of younger refolding. The S planes show a tight clustering that reflects cor stant orientation across the region. The I shaped maximum of the S_{3S} plot represen systematic changes in orientation; in the ex treme south, the strike of S_{3S} remains constar as the dip changes. The pattern of S_{3N} reflec the constant steep dip but changing strike c these surfaces.

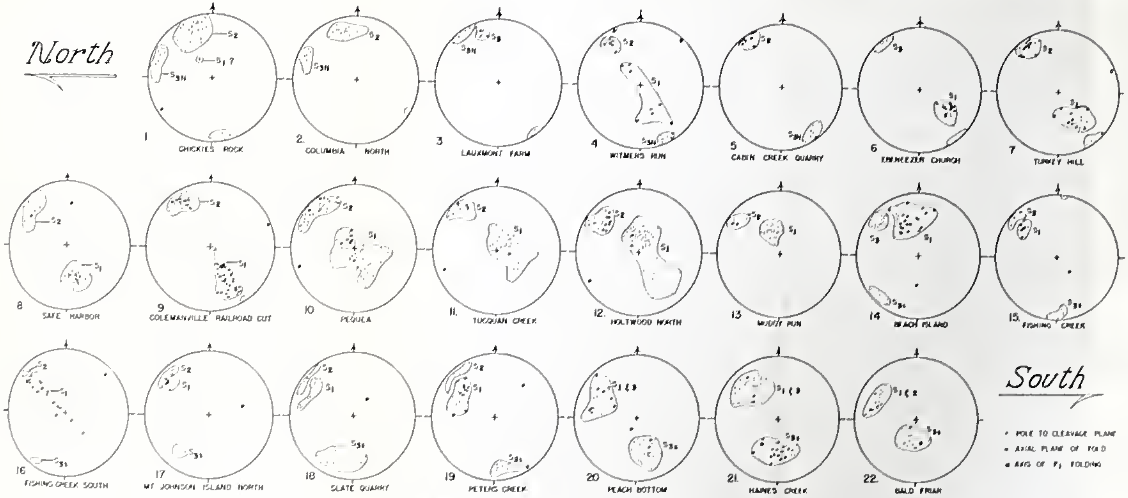
The S_4 occurs locally as axial planes of zon of kink banding that deform all other surface These zones may be several inches apart an spaced at intervals of a few feet to a few hur dred feet. They have been omitted from Pla 1 because of their sparse occurrence in any o outcrop and their variable orientation.

The average attitudes of the S-surfaces each station are presented in Table 1. By glan ing down the lists one can note the progressiv but systematic changes in orientation acro the region.

Dominant Zones of the Various Patterns

Listing the planes, their orientation, ar their character does not convey complete the changing aspect of deformation across tl region. Ordinarily one of the S-surfaces is d veloped strongly enough to obscure the othe Thus, dominant zones of the various S-surfac can be recognized. Failure to recognize change in dominance of S-surfaces can resu in the mistaken conclusion that a sudd change in the orientation of the fold patte has taken place.

The areas in which the S-surfaces and pa



DIAGRAMS OF CLEAVAGE AND AXIAL-PLANE ORIENTATIONS IN A NORTH SOUTH SECTION ALONG SUSQUEHANNA RIVER

FREEDMAN AND OTHERS, PLATE 1
Geological Society of America Bulletin, volume 75

ular kinds of folding dominate are, from rth to south: S_2 and F_2 folding—The Lancas- r-Columbia Valley; S_1 and F_1 folding—The artic Line through the Tucquan anticline d the Peach Bottom syncline to Peters reek; S_{3S} and F_{3S} folding—Peters Creek ross the state line to Bald Friar.

Recognition of these zones of dominance ould clarify further investigations in the gion.

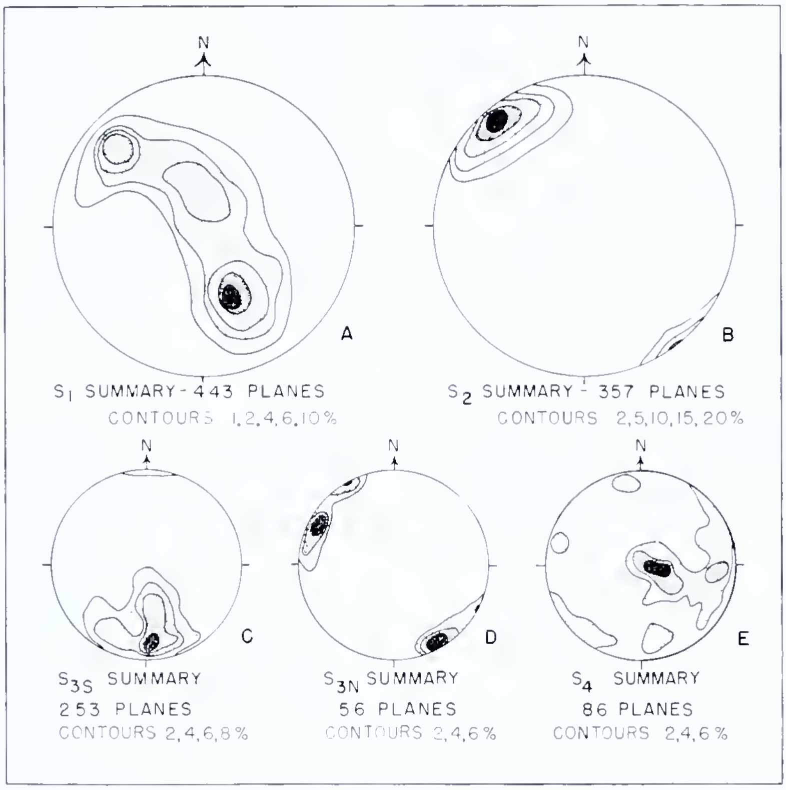


Figure 4. Summary diagrams of S-surfaces

attern of F_1

The F_1 fold pattern is characterized by oclinal folding that involves flowage and the evelopment of major schistosity. Locally, uartz lenses, layers, or pods follow S_1 and the oclinally folded S_0. The S_1 includes the domi- ant schistosity of the region and is defined by ajor reorientation and recrystallization of the icas. Metamorphic conditions in D_1 were rgely within the greenschist facies but locally nged into the epidote-almandine facies. The ntire mass of the rocks seems to have under- one flowage along planes parallel to S_1, a owage that has transposed most of the S_0 lanes into parallelism with it. All subsequent deformations have been at lower metamorphic conditions, involving less flowage and recrystallization and relatively more shear folding and bending of mica plates (Pl. 5, figs. 1, 2).

The F_1 folds are widespread but not easily distinguishable north of the Martic Line. Very few F_1 flowage folds are found in the brittle thick-bedded quartzites at stations 1, 2, and 3. Farther south at Witmers Run (station 4), several F_1 folds are discernible in the Conestoga Limestone beneath a camouflage of intense S_2 and S_3. At one place in this outcrop, the axial plane of an F_1 isoclinal flow fold can be observed tightly folded by the younger deformation. Similar F_1 folds are present in the Conestoga Limestone of the Lancaster–Columbia Valley but are difficult to discern among the younger fold patterns.

S_1 crosses the Martic Line with little or no change in orientation or character (Cloos and Hietanen, 1941). It becomes increasingly more prominent southward from the Martic Line and shows evidence of gross overturning. The rotated character of S_1 and F_1 in this area is illustrated by Figure 2 of Plate 2 and Figure 3 of Plate 2.

Throughout most of the Turkey Hill-Safe Harbor area (stations 6–8), bedding in Wissahickon Formation is too poorly defined to permit one to distinguish F_1 readily. Axial planes parallel the dominant schistosity (S_1) at Turkey Hill above pole 1007, and at Safe Harbor at pole 888, where brown-weathering, calcareous quartzites make the folds readily visible. There, the axial planes of individual flow or shear folds persist for tens of feet separated from each other by a few inches to several yards. The plots of stations 6, 7, 8 and 9 (Pl. 1) are very similar in spite of differing locations in Wissahickon Formation and Conestoga Limestone on opposite sides of the Martic Line. This proves that F_1 (plus all subsequent deformations) is younger than the Martic contact, whatever the origin of the contact may be.

Table 1. Average S-Surface Orientations Across the Region
(Values represent centers of cones of spread of plotted poles)

Station	S_1 Strike	S_1 Dip	S_2 Strike	S_2 Dip	S_3 Strike	S_3 Dip	S_4 Strike	S_4 Dip
North-west					S_{3N}			
1. Chickies Anticline	N. 55° E.	30° SE.	N. 70° E.	75° SE.	N. 25° E.	80° SE.		
2. Columbia North			N. 80° E.	65° SE.	N. 25° E.	80° SE.	N. 15° E.	70° N
3. Lauxmont Farm			N. 70° E.	70° SE.	N. 50° E.	85° SE.	N. 10° E.	25° N
4. Witmers Run	N. 50° E.	35° NW. and SE.	N. 50° E.	75° SE.	N. 65° E.	80° NW.		
5. Cabin Creek Quarry			N. 50° E.	85° SE.	N. 55° E.	80° NW.	N. 10° W.	80° S
6. Ebenezer Church	N. 35° E.	45° NW.	N. 50° E.	85° SE.				
7. Turkey Hill	N. 60° E.	45° NW.	N. 55° E.	85° SE.				
8. Safe Harbor	N. 75° E.	45° NW.	N. 45° E.	70° SE.				
9. Colemanville	N. 70° E.	50° NW.	N. 60° E.	75° SE.				
10. Pequea	N. 25° E.	10° NW.	N. 50° E.	75° SE.				
11. Tucquan Creek	N. 30° W.	0° SE.	N. 50° E.	70° SE.				
12. Holtwood North	N. 70° W.	25° SE.	N. 40° E.	70° SE.	S_{3S}			
13. Muddy Run	N. 75° E.	30° SE.	N. 40° E.	80° SE.				
14. Beach Island	N. 75° E.	50° SE.	N. 40° E.	70° SE.	N. 50° W.	80° NE.		
15. Fishing Creek	N. 40° E.	60° SE.	N. 40° E.	85° SE.	N. 85° E.	80° NW.	N. 75° E.	30° N
16. Fishing Creek South	N. 40° E.	60° SE.	N. 40° E.	80° SE.	N. 60° W.	75° NE.		
17. Mt. Johnson Island North	N. 40° E.	70° SE.	N. 40° E.	85° SE.	N. 55° W.	65° NE.		
18. Slate Quarry	N. 50° E.	70° SE.	N. 65° E.	80° SE.	N. 80° W.	60° NE.	Horizontal	
19. Peters Creek	N. 50° E.	65° SE.	N. 45° E.	75° SE.	N. 85° E.	55° NW.	N. 35° E.	45° N
20. Peach Bottom	N. 30° E.	55° SE.	N. 30° E.	55° SE.	N. 70° E.	50° NW.		
21. Haines Creek	N. 50° E.	60° SE.	N. 50° E.	60° SE.	N. 85° E.	45° NW.		
22. Bald Friar	N. 30° E.	60° SE.	N. 30° E.	60° SE.	E–W	25° N.		
Southeast								

Southward, the dip of S_1 flattens across the younger F_2 Tucquan anticline. The anticlinal crest is several miles wide with essentially horizontal S_1 between Pequea and Holtwood (Fig. 6, stations 10, 11, 12). The nearly horizontal isoclinal folds with axial planes m closely spaced than those farther north illustrated in Figures 3 and 4 of Plate 3.

South of Holtwood (Fig. 2), the southw dip of S_1 gradually steepens to vertical in Peach Bottom Syncline. This is demonstra by the progressive migration of F_1 poles tween stations 13 and 17 (Pl. 1). In the area the Peters Creek Schist, bedding is more clea defined so that F_1 may be recognized readi especially at Beach Island (station 14) and the signal light just south of Mt. Johnso Island (station 17.5 at pole 469).

The S_1 continues southward, dipping stee with the same orientation, to become the do nant slaty cleavage in the abandoned sl quarries in the Peach Bottom syncline(stati 18). Agron (1950) recognized this cleavage being associated with the early folding of t Peach Bottom syncline.

South of Peach Bottom syncline, S_1 is t dominant foliation of the rocks and is alm parallel to bedding (S_0). The F_1 is obscured well-developed F_3. One F_1 occurs just south e cable barrier, south of Peach Bottom at le 396.

For most of the distance from Peach Bottom Bald Friar (stations 20–22) graded bedding licates stratigraphic tops to the south. Several cal reversals of tops to the north occur for dths of a few hundred feet across strike. For ample, the first tunnel south of Peach Bottom ows tops to the north from poles 388 to 378. is relationship suggests isoclinal folds in the ters Creek Schist on a scale comparable to at of the major fold in the Peach Bottom cline. The reversals from zones of "right-le up" to "upside-down" graded beds occur ruptly with almost no visible curvature. This eming anomaly was partially resolved by the scovery that here the isoclinal fold axes (A_1) nge down the dip of S_1. Hence, the only posures in the railroad cuts are folds with eply plunging axes that cannot show the rvature in passing from one fold limb to the er.

he A_1 and Associated Lineations

The A_1 (fold axes) can be located by careful rch in most areas. A large outcrop commonly lds one to five fold axes. The approximate aximum of these fold axes for stations where ta could be obtained is recorded as a star on e plots of Plate 1. As previously noted, A_1 the only fold axis in the region that has a ctonically independent orientation. All unger axial orientations can be derived from tersections of deformational planes.

The A_1 lies in S_1 but has variable orienta-ns across the region. It tends to plunge steep- down the dip in the south in accord with nilar steeply plunging fold axes in adjacent eas of Maryland (Jonas, 1937) and Delaware Vard, 1959). In the south, strongly developed eations down the dip of S_1 lie parallel to A_1 l. 1) but are strongly refolded by F_3. These ×1 lineations appear as closely spaced lines on .

In the north, A_1 and associated lineations are arly horizontal paralleling the strike of S_1. etween the north and south portions is a mile wide transition zone (stations 13–19) which horizontal, steep, or transitional unges dominate local areas.

he F_2 Pattern

The S_2 can have some mica recrystallization sociated with it, but more commonly it is arked by planes of bent or distorted micas and slip surfaces associated with slip or shear folding. It varies with lithology but is best developed in incompetent phyllites and slates. Throughout the area it has a fairly constant orientation of about N. 50° E., 80° SE. (Fig. 4; Pl. 2, fig. 2; Table 1). In the south, S_2 disappears as a separate structure (Pl. 1, stations 20, 21, 22) where S_2 and S_1 merge in orientation beneath a camouflage of strongly developed S_3s.

The Chickies anticline, a complex structure at the north end of the section, involves development of anomalous S_1 across a pre-existing Ordovician fault zone with subsequent modification and enhancement by D_2 structures. A fuller discussion of structures in the Chickies anticline is being prepared as a separate paper.

Southward in the Lancaster–Columbia Valley, S_2 is the dominating structure. In the Conestoga Limestone, metamorphism associated with F_2 created phyllitic surfaces. Along Susquehanna River S_2 is so strongly developed in the Conestoga Limestone that careful search is necessary to find remnants of F_1 (*e.g.*, station 4).

South of the Martic Line, in the Wissahickon Formation and Peters Creek Schist, S_2 appears as thin zones of rotation of the mica flakes in the pelitic rocks or as unhealed cleavage fractures in the more quartz-rich rocks. All gradations exist between these two types of S_2. Slip folding parallel to S_2 is common (*e.g.*, Turkey Hill, station 7 near pole 1013).

Microscopically, S_2 appears in almost all thin sections from south of the Martic Line. The planes show minor recrystallization but are mostly planes of bending, flexing, or shredding of larger pre-existing mica flakes.

Southward from Holtwood, orientations of S_2 and S_1 merge and are difficult to distinguish. In pelitic layers the two cleavages intersect to reveal their mutual age relationships. As far south as Peters Creek, where the difference in dip is only 5–10°, it is possible to distinguish them as two sets of planes.

In the Peach Bottom Slate, S_2 is a secondary slaty cleavage that varies slightly in both strike and dip from the earlier S_1 slaty cleavage. Here S_2 is not as smooth as S_1 in which the minerals have stronger orientation.

South of Peters Creek, the authors were unable to separate S_1 from S_2 through the undulating overprint of intense S_3s and F_3s. The sense of displacement on S_2 reverses over distances of a few inches to a few hundred feet, reflecting local transitions from open anticlines to open synclines. Thus the pattern of F_2 folds cannot be derived from the simple sense of displacement on these surfaces. The best large fold indicators are the broad changes in dip imposed on S_1. These are warped into the Tucquan anticline and Lancaster–Columbia synclinorium with half wave lengths of approximately 7 miles. Eastward along strike, the S_2 Tucquan anticline exposes Precambrian basement in the core of Mine Ridge (Fig. 1). The strike of S_2 parallel to this basement uplift, its genetic relationship to the folds, and its constant orientation over the lower Susquehanna region suggest that S_2 is a widespread pattern related to basement folding of the region.

The F_3 Pattern

There are two distinct areas where surfaces younger than S_2 occur; S_{3N} in the north and S_{3S} in the south. The two areas are discuss separately because it is uncertain whether th belong to the same deformational episode.

The S_{3N} is a fracture cleavage showing recrystallization or rehealing of fractures a only rare folds. Locally, in the massive quar ites of Chickies anticline the S_{3N} fractu strike N. 25° E. and are spaced as closely as h a centimeter. Southward, in Columbia Vall the strike changes to N. 50° E. to become proximately parallel to that of S_2. Fortunate the dip of S_{3N} also changes, facilitating sepa tion of the two classes of structure at Cal Creek quarry (station 5). These progress changes in orientation are illustrated by migration of the S_{3N} maxima in plots of stati 1–5 (Pl. 1).

PLATE 2. F_1 AT CHICKIES ANTICLINE AND S_1, S_2, AND F_1 AT TURKEY HILL ALONG SUSQUEHANNA RIVER, PENNSYLVANIA

Figure 1. F_1 fold, Chickies anticline (station 1). Isoclinal syncline with axial plane N. 52° E., 30° S and fold axis, N. 65° E., 5° SW. is composed of thin-bedded quartzite of Chickies Formation. F located in abandoned trolley line cut over crest of Chickies anticline (looking northeast)

Figure 2. S_1 and S_2 cleavages, Creswell Station-Turkey Hill (station 7). S_1 cleavage, N. 60° E., 50° N cut by S_2 cleavage, N. 60° E., 85° SE. Cleavages developed in chlorite-albite-quartz schists of Wi hickon Formation, are located on upper level of Pennsylvania Railroad above electric pole num 1018 of lower level (looking northeast).

Figure 3. F_1 folds, Creswell Station-Turkey Hill (station 7). Isoclinal folds with axial planes N. 70° 50° NW., and fold axis N. 65° E., 5° SE. is composed of carbonate-bearing chloritic quartzites (l quartz lenses) of the Wissahickon Formation. View, looking northeast, is in same location as Figur located one quarter of a mile southeast of Martic Line at pole 1011.

Figure 4. F_1 antiformal syncline in the Wissahickon Schist Creswell Station-Turkey Hill (station Fold with axial plane N. 70° E., 56° NW., and fold axis N. 65° E., 12° SW., is cut by nearly vertica cleavage. Graded bedding in the carbonate-bearing quartzite beds indicate that top is toward cente fold. It is located on upper level of the Pennsylvania Railroad above electric pole 1007, on lower l (looking northeast).

PLATE 3. F_1 AND F_2 FOLDS AT SAFE HARBOR, COLEMANVILLE RAILROAD CUT, AND AT AXIS OF TUCQUAN ANTICLINE, ALONG SUSQUEHANNA RIVER, PENNSYLVANIA

Figure 1. F_1 folds, Safe Harbor (station 8). Isoclinal folds with axial plane N. 75° E., 48° NW., and axis N. 10° E., 35° NE., are in carbonate quartzites and albite-biotite-muscovite schists in Wissahic Formation. Folds located on lower level of Pennsylvania Railroad near electric pole 888, opposite Harbor power plant

Figure 2. F_1 and F_2 folds, Colemanville (station 9). F_1 isoclinal flow folds outlined by siliceous ma beds half an inch thick; axial plane, N. 62° E., 35° NW., and fold axis nearly horizontal (axial pla is gently inclined from upper right to lower left). The F_1 folds are cut by F_2 slip folds, axial plane, N. 0 E., 80° SE., and fold axis nearly horizontal. The folds are in Conestoga Limestone, just north of he Martic Line, located 0.9 mile west of high railroad trestle of Pennsylvania Railroad across Pequea C ek at Martic Forge (looking northeast).

Figure 3. F_1 folds at Pequea (station 10). Axial plane of F_1 isoclinal flow folds is nearly horizontal. F ds are distinguished in the chlorite-muscovite-quartz schists of Wissahickon Formation by local qu tz lenses. View, looking northeast, is in road cut of highest asphalt road at Pequea.

Figure 4. F_1 folds at Tucquan Creek (station 11). Quartz lenses in chlorite-albite schists of Wissahic n Formation outline F_1 isoclinal flow folds with nearly horizontal axial planes and fold axes. Locate in railroad cut near mouth of Tucquan Creek (looking northeast), pole 708

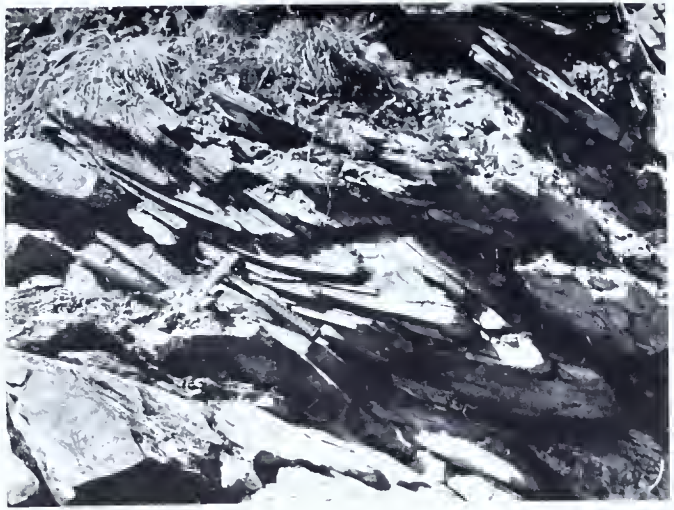


Figure 1

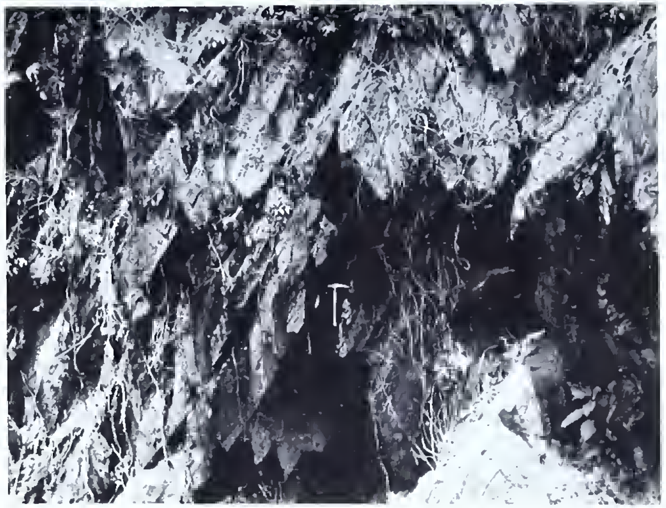


Figure 2

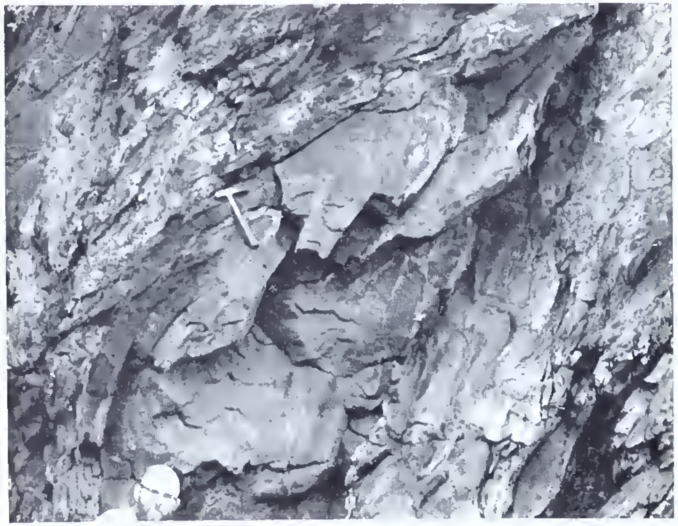


Figure 3

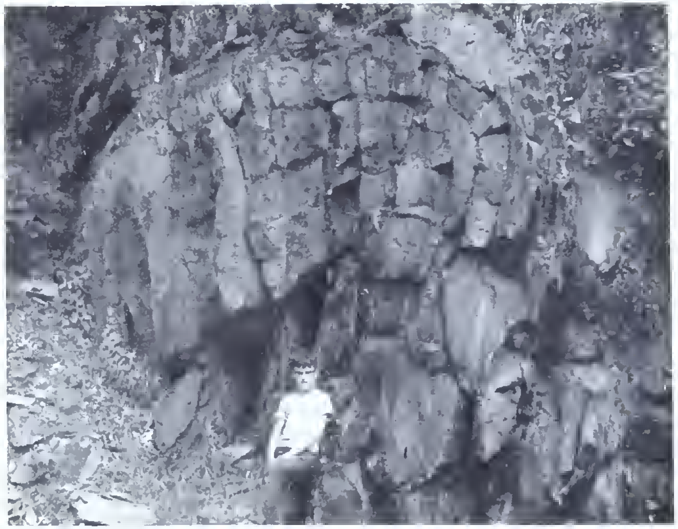


Figure 4

F_1 AT CHICKIES ANTICLINE AND S_1, S_2, AND F_1 AT TURKEY HILL
ALONG SUSQUEHANNA RIVER, PENNSYLVANIA

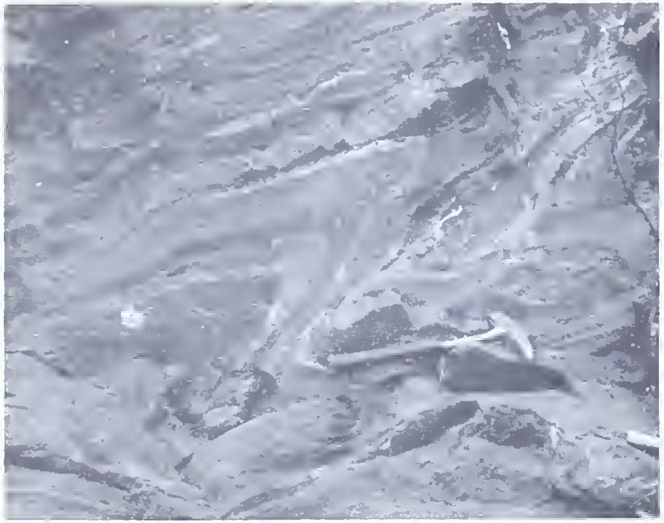


Figure 1

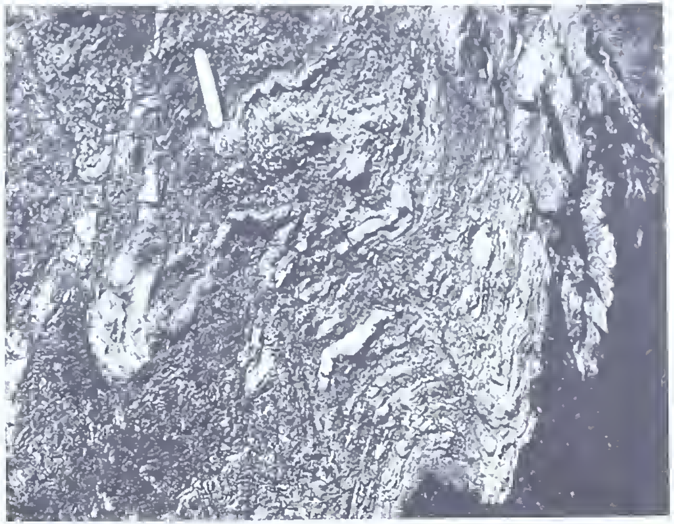


Figure 2

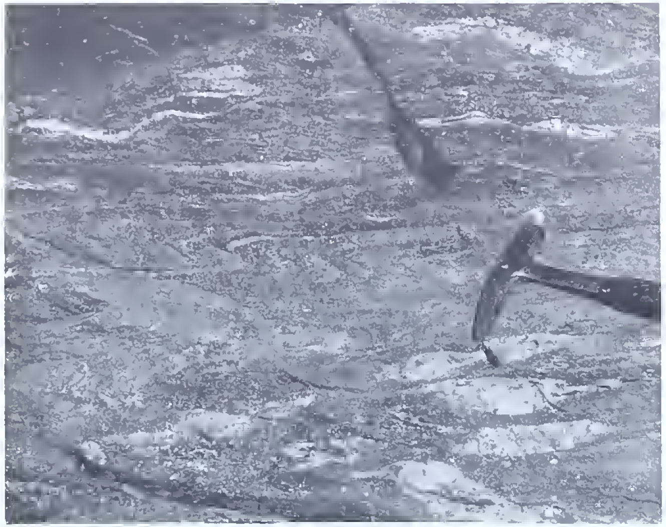


Figure 3

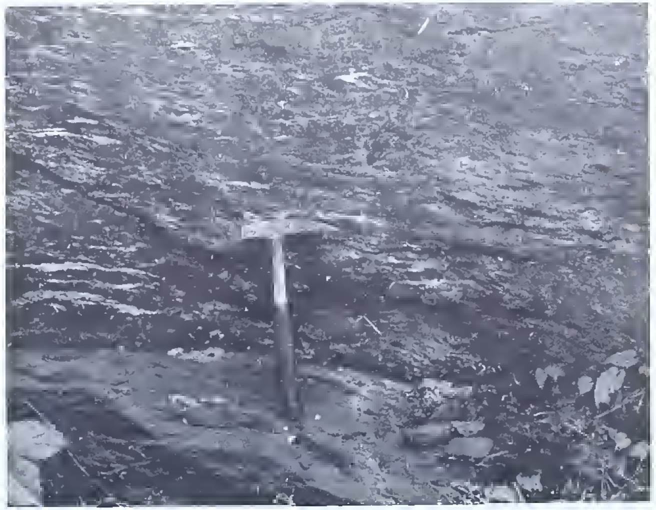


Figure 4

F_1 AND F_2 FOLDS AT SAFE HARBOR, COLEMANVILLE RAILROAD CUT, AND AT

FREEDMAN AND OTHERS, PLATE 4
Geological Society of America Bulletin, volume 75

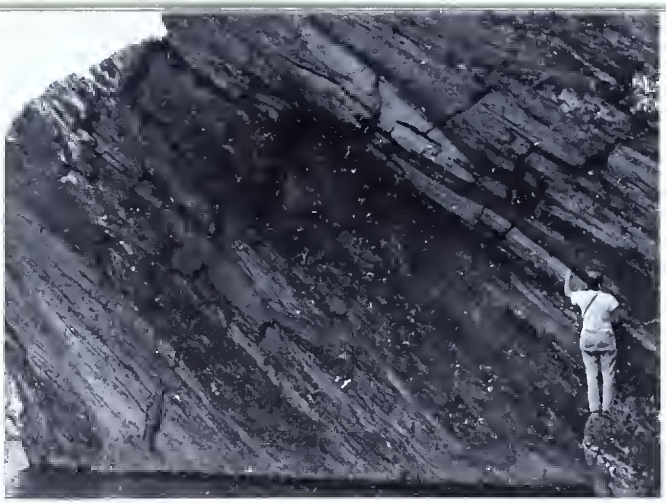


Figure 1

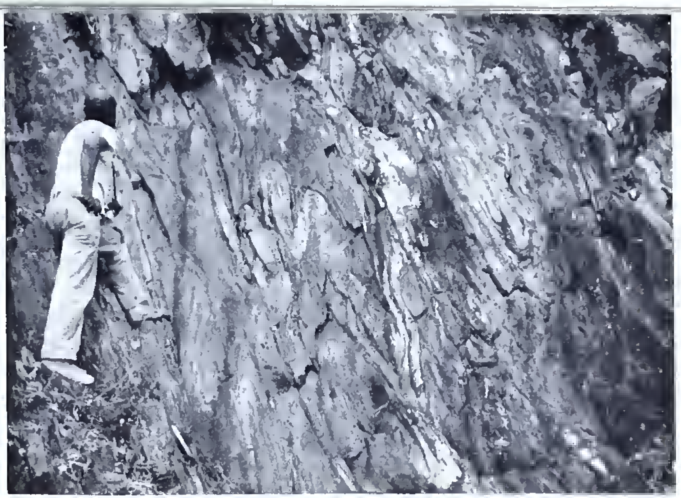


Figure 2

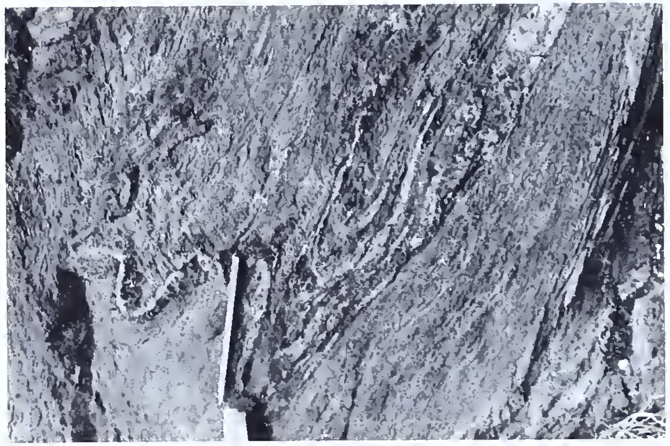


Figure 3

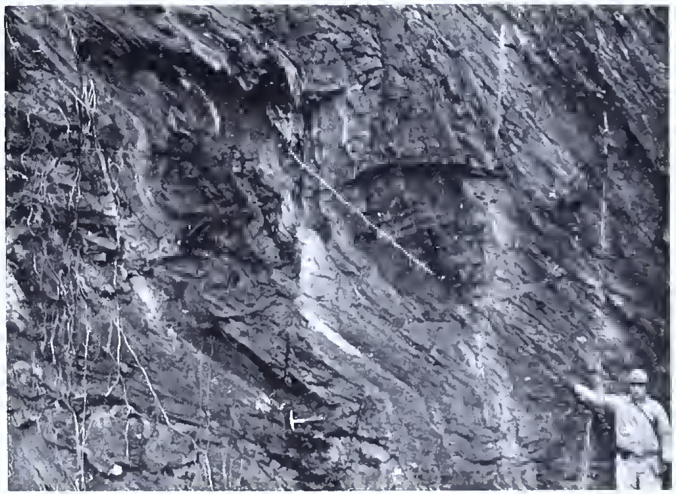


Figure 4

FOLDS AND CLEAVAGE AT BALD FRIAR, ALONG
SUSQUEHANNA RIVER, PENNSYLVANIA

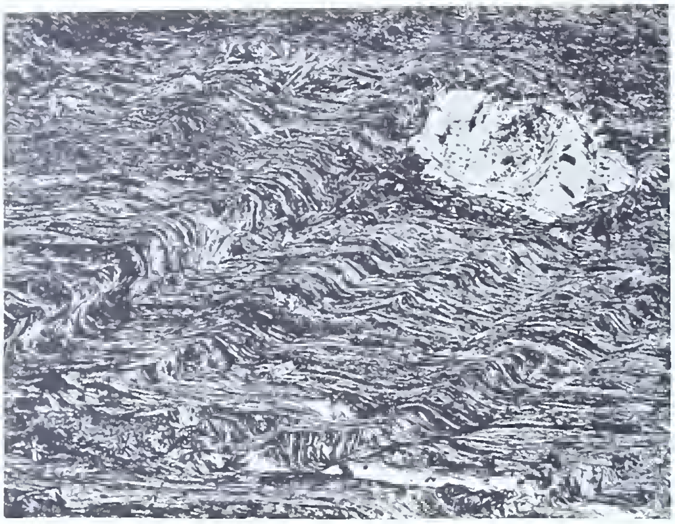


Figure 1

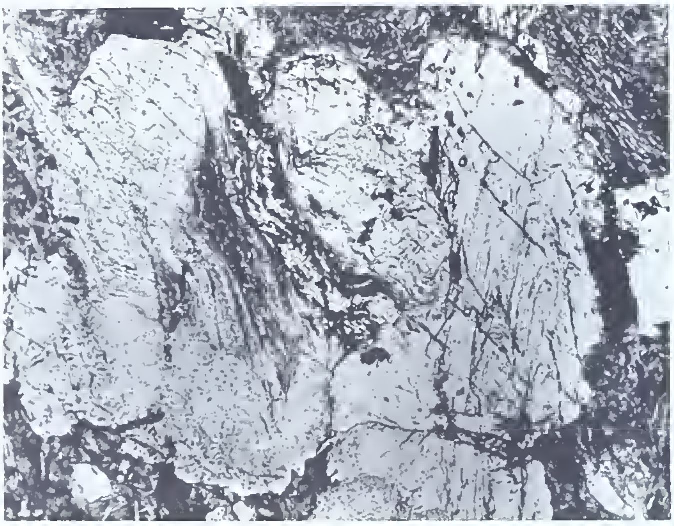


Figure 2

PHOTOMICROGRAPHS SHOWING PORPHYROBLASTS FROM WISSAHICKON FORMATION, PENNSYLVANIA, WITH RELICT CLEAVAGE AND S_1 FOLDED TO F_2 AND S_2

n the summary plot of 56 S_{3N} orientations
g. 4D), there are too few points, and the
ions are improperly spaced to permit one to
w significant conclusions. South of the
rtic Line, no S_{3N} were distinguishable.
ether they do not exist or are merely ob-
red by merging in orientation with S_2 is un-
own.

$_{3S}$ appears in the lower Susquehanna as a
t cleavage at Beach Island and Fishing
ek (Pl. 1, stations 14, 15), becoming more
ngly developed southward with increasing
nsity of folding. South of Peters Creek, S_{3S}
F_{3S} dominate all other structures (Pl. 4,
4). In the area of S_{3S} development, its
ke shifts progressively from northeast in the
th to east-west in the south, and the dip
nges from nearly vertical in the north, at
hing Creek (Pl. 1, station 15) to nearly
izontal in the south, at Bald Friar (Pl. 1,
ion 22). Figure 4C reflects these progressive
nges by an L-shaped partial girdle.

he F_{3S} are slip folds in which the cleavage
s through 20° locally and the distance be-
en axial planes ranges from 1 mm to 1 m. The
l pattern creates a series of structural ter-
es and risers ranging in magnitude up to several hundred feet. The lower right corner of Figure 6 shows an idealization of the fold pattern and changing dips of F_{3S}.

The S_4 Characteristics

The S_4 occurs locally as variably oriented (Table 1) 2–6-inch wide planar zones spaced at intervals of a few feet to a few hundred feet. Within the planar zone older *S*-surfaces are bent into *S*-shaped folds by differential movements on opposite sides of the plane.

Along strike the zones may turn into faults of small displacement, small brecciated veins, or simple joints. Most of the planes have variable orientations within approximately 30° of the ac plane, and most commonly have strike-slip displacement. These features are well developed in the Conestoga Limestone in the vicinity of Lancaster (Wise and Kauffman, 1960, p. 60–63) where they are interpreted as structures transitional into ac jointing.

Another type of S_4 occurs in the vicinity of the Peach Bottom Slate quarry (station 18) as a young, nearly horizontal, closely spaced slip cleavage. These planes may represent a different time and a different stress from the other type of S_4 but are included for simplicity

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PLATE 4. FOLDS AND CLEAVAGE AT BALD FRIAR, ALONG SUSQUEHANNA RIVER, PENNSYLVANIA

ure 1. F_1 isoclinal flow folds, Sicily Island (near station 14) with axial plane N. 75° E., 50° SE., and
old axes N. 5° E., 50° SW. Quartzite beds in albite-chlorite schists of transitional zone between Wissa-
ickon Formation and Peters Creek Formation are located on northeast side of Sicily Island in Susque-
anna River, 1½ miles northwest of Fishing Creek.

ure 2. F_1 isoclinal flow folds, Mt. Johnson Island (between stations 17 and 18), with axial planes N.
0° E., 70° SE., and fold axes N. 40° E., 20° NE. Quartzite beds in Peters Creek Formation show the
reat complexity of isoclinal F_1 folds in the southeastern portion of the section. These folds are located
in railroad cut) near signal light, one quarter of a mile southeast of Mt. Johnson Island looking north-
ast, pole 455.

ure 3. F_1 folds and S_{3S} cleavage, Haines Creek (station 21). Quartz veins outline F_1 folds plunging
teeply (60°) southwest. The S_{3S} slip cleavage intersects the F_1 axial planes at high angles. View is to
ortheast face of the railroad cut near southeast end of first tunnel. South of Peach Bottom at railroad
ole 376

ure 4. F_{3S} folds, Bald Friar (station 22). F_{3S} slip folds with axial plane N. 85° E., 25° NW., located
ear pole 327 just northwest of third tunnel southeast of Peach Bottom. View (looking northeast) shows
ypical alternating beds of feldspathic quartzite and chlorite-muscovite schists of Peters Creek Forma-
ion.

PLATE 5. PHOTOMICROGRAPHS SHOWING PORPHYROBLASTS FROM WISSAHICKON FORMATION, PENNSYLVANIA, WITH RELICT CLEAVAGE AND S_1 FOLDED TO F_2 AND S_2

ure 1. Photomicrograph of chlorite-muscovite-quartz schist with rolled albite porphyroblast showing
elict cleavage from Wissahickon Formation. S_1 (horizontal), F_2 and faint S_2, × 80

ure 2. Photomicrograph of albite porphyroblasts from Wissahickon Formation showing relict F_1 and
S_1 of chlorite and muscovite flakes, × 80

and from lack of additional data. The two classes of S_4 are responsible for the scatter of maxima on figure 4E, a figure with too few data to be statistically significant.

LINEATIONS

Many lineations were measured along Susquehanna River. One class of these lineations, A_1, has been discussed previously under F_1 because of its relatively independent orientation in the regional tectonic pattern. All other lineations are related to intersections of more prominent S-surfaces. A plot of the lineations at an outcrop (exclusive of A_1 axes) consequently has the appearance of a cluster of points along a great circle representing the plane of the major foliation (Fig. 5). Fold axes parallel to the intersections of less prominent S-planes, *e.g.* $A_{2\times3}$, are rarely seen.

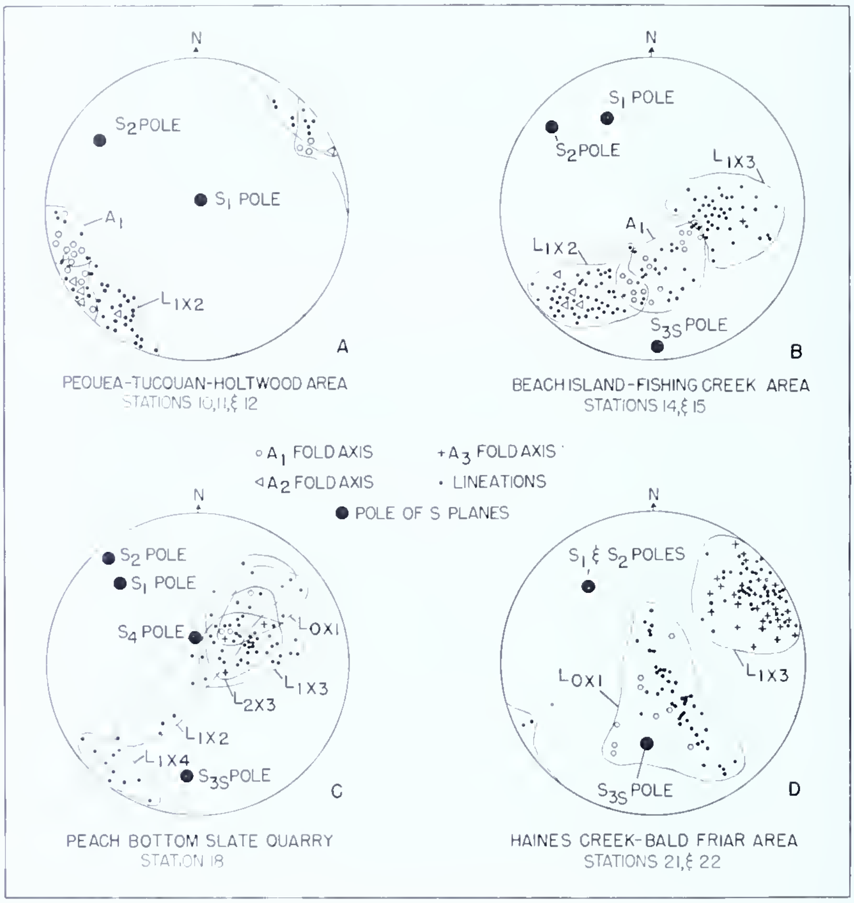

Figure 5. Diagram showing orientation of fold axes and lineations in selected locations

A useful clue to finding poorly developed S-surfaces is the presence of minor lineations on the prominent S-surfaces. These lineations can be found readily in most outcrops, but mu more careful search is ordinarily necessary find the planes causing the lineations. General these fainter planes are well developed only the metamorphosed pelites.

In order to illustrate variations in develc ment of linear structures, the lineation patte of four typical areas will be discussed. Figu 5A includes stations 10, 11, and 12 (Pequ Tucquan-Holtwood area), across the Tucqu anticline. In the field it was possible to c tinguish A_1 and $L_{0\times1}$ from A_2 and $L_{0\times2}$ by t style of folding and dip of associated ax planes. The two types of lineation differ average strike but plunge gently southwe ward along with the Tucquan anticline on whi they are located. The strike of the dependen oriented A_2 and $L_{0\times2}$ is along the line of int section of the S_1 and S_2 planes.

Figure 5B is a composite of the Beach Isla (station 14) and Fishing Creek (station 1 areas showing a partial girdle of lineations. T

e represents the plane of the prominent
schistosity that has the independently
nted A_1 and $L_{0\times1}$ lineations within that
e. Intersections of isoclinally folded bedding
the less prominent S_2 and S_3 define the
$_2$ and $L_{0\times3}$ respectively within the S_1 plane.
gure 5C, the Peach Bottom Slate quarry
ion 18), is a challenge because: bedding is
ly defined; S_2 is also a slaty cleavage similar
haracter and orientation to S_1; and S_4 is
lly a good slip cleavage.

he S_4 surfaces generate four additional
; of potential intersection in an already
plex picture ($L_{0\times4}$, $L_{1\times4}$, $L_{2\times4}$, $L_{3\times4}$). As
igure 5B, all observed lineation intersec-
s with S_1 and S_2 form a girdle in those
es. As both S_1 and S_2 vary slightly in strike
dip, $L_{1\times2}$ has quite variable orientation
in their planes and produces the large $L_{1\times2}$
le. The intersections of S_3s with the major
vages define the appropriate $L_{1\times3}$ and $L_{2\times3}$
in the major cleavage planes. The rela-
ly horizontal S_4 results in a nearly hori-
al lineation ($L_{1\times4}$) as it intersects the
ly dipping S_1 plane. This lineation picture
ill incomplete since only five of the ten
ible intersection lineations were found.
vever, the picture helps explain the ex-
ely complicated lineation map of the
h Bottom syncline presented by Agron
0).

igure 5D of the Haines Creek-Bald Friar
(stations 21, 22) is reasonably simple.
re are two basic clusterings of intersection
tions with associated fold axes. The inde-
lently oriented A_1 and the $L_{0\times1}$ inter-
ons plunge dominantly south-southeast
ariable angles to form a girdle reflecting the
nges in dip caused by later intense D_3 de-
ation. The A_3s and the $L_{1\times3}$s plunge east-
heast along the line of intersection of S_1
S_2 with S_3.

SSIBLE ERRORS

any problem involving correlation of data,
possibility of miscorrelation exists. The
ors are reasonably certain of the correla-
s of *S*-surfaces presented in this paper but
that the inherent difficulties or possible
k points in the correlation should be men-
ed.

he interpretation of the Chickies anticline
mplex D_1 and D_2 structures is debatable.
orientation of the dominant cleavage at
kies anticline is in accord with the regional
attern. To the north F_1 flow folds in Cambrian and Ordovician limestones have horizontal axial planes that terminate abruptly against the frontal fault at the north edge of the Chickies anticline. On these grounds, the structure has been interpreted as a D_2 fold disrupting a nearly horizontal F_1 system.

An alternate interpretation requires the Ordovician fault recorded in the Cambrian strata unconformably beneath the Conestoga Limestone, to disturb the local F_1 flow pattern in the brittle quartzite and to cause anomalous S_1 orientations. Subsequent reactivation of the Chickies fault and fold structures during D_2 time would have juxtaposed deeper and shallower S_1 structures across the frontal fault zone. Acceptance of the alternate interpretation at this one station would not significantly alter the regional picture.

The interpretation of the dominant folds of the Lancaster–Columbia Valley as F_2 implies that S_1 has been obliterated in many areas. Careful search, though, reveals S_1 in many outcrops of Conestoga Limestone, *e.g.*, in the Colemanville railroad cut (station 9).

To the south, S_3s becomes increasingly prominent relative to S_1 and S_2. It is possible that the latter surfaces of essentially the same structural character could be nearly the same age with one merging into the other.

THEORETICAL CONSIDERATIONS

General Statement

Up to this point the authors have tried to present field data and observations with minimum interpretation. Problems and implications of a more speculative nature have been reserved for treatment here.

Roots of Nappes Problem

Nappe structure and recumbent folding are well developed in the Great Valley of Pennsylvania (Geyer and others, 1958) and have been traced southward to the vicinity of Chickies anticline (station 1) by published (Wise, 1958) and unpublished work of Franklin and Marshall College personnel. If roots to these nappes exist, they must be situated somewhere between the regions of horizontal flowage and the more vertical structures of the Inner Piedmont that is within the area described in this paper.

Within the area, S_1 constitutes the only structure transitional from vertical in the southeast to horizontal in the northwest. The axial trends of A_1 and the style of flow folding are almost identical to that of the recumbent flow folds to the north. The authors suggest that S_1 constitutes the flow-folded roots of the nappes of the Great Valley that extend for 30 miles across strike from a source of essentially vertical flowage in the Inner Piedmont (Fig. 6A). The pattern beneath the overprint of younger deformations is essentially that of the Pennine Nappes of the Alps.

Inherent in this interpretation is the identification of F_1 in the Turkey Hill-Safe Harbor area (stations 7, 8, 9) as synformal anticlines and antiformal synclines, an interpretation supported by graded bedding in these outcrops. Either initial dip of the flow planes or younger deformation has rotated these folds past recumbency on the north flank of the Tucquan anticline (Fig. 6A). Structures of this type are illustrated in Figure 3 and 4 of Plate 2. It must be emphasized that it is merely the flow *pattern* that is past recumbency and has been overturned and not the entire stratigraphic column. Furthermore, it does not imply that tectonic transport moved rock masses 30 miles across strike but rather that a system of uniform flow movements penetrated the rock mass for that distance.

Direction of Tectonic Transport

The directions in which rock masses actually move during deformation is of fundamental tectonic importance. The problem is most complex for D_1 where A_1 lies in the dip of S_1 in the south but parallel to its strike in the north. The two areas are separated by a 5-mile-wide transition zone. In the north, the horizontal A_1 is interpreted as a tectonic *b* structure parallel to the regional fold axis directions and perpendicular to bedding-plane slickensides and other linear movement indicators. Thrusting and flow directions in this area are toward the northwest. If all D_1 was part of a single movement pattern as suggested by the regional continuity of S_1 surfaces (Fig. 6A), A_1 in the south would represent tectonic *a* with movement up the dip of S_1. The transition zone between these two areas could be interpreted as a change from *a* to *b* tectonites as described by Cloos (1947) in carbonates of the nearby South Mountain area.

An alternate explanation of the steeply plunging A_1 in the south is D_1 strike-slip shearing or flowage restricted to the more plastic core region of the Appalachian Piedmont. No additional evidence of D_1 strike-slip movement was noted. For D_2, the only evidence of stri slip movement is systematic displacement al S_2 in the Port Deposit quarry. The D_4 characterized by small strike-slip displaceme with both right-and left-lateral movem perpendicular to regional strike. Widespr numerous small faults and gouge zones throu out the area postdate most or all *S*-surfaces a are characterized by nearly horizontal slick sides. All of these real or possible strike- features seem to play only a minor role in tectonic transport across the structural grai the country.

The D_2 appears to represent nearly vert movements up or down the steeply dipping planes to produce slip folds. Accordingly, v little horizontal transport took place in t basement-related deformation.

The F_{3S} slip folding has a peculiar pattern the "roots-of-recumbent-folds" concept is plied to these folds, the more steeply dipp roots would be in the north and tectonic tra port would be from north to south (Fig. 6 This is weakly supported by a top-to-the-so sense of gross displacement in the zones of m intense slip development, the "risers" of steplike folds (Fig. 6C). The evidence is we but the suggestion remains of north to so transport in D_{3S}.

A common concept of structural geolog that most fold axes bear some rational relati ship to directions of tectonic transport. In lower Susquehanna region this is true for independently oriented A_1, but not for your axes that are defined by simple intersection *S*-planes. The independent variable is orientation of the *S*-plane along which ac transport and shearing takes place. Where plane crosses an older *S*-surface a depende oriented fold axis results with little relations to the true direction of transport on the acti moving *S*-surface.

Rock Behavior Under Deformation

A sharp contrast exists between the beha of similar rocks under different deformat and the behavior of different rocks under same deformation. A single *S*-plane is a throu going surface created by one stress system, it may take many forms dependent on lithol Locally, S_2 is a flow or slaty cleavage in bonates and slates, a slip cleavage in schist, a fracture cleavage in quartzite. All these cl ages seem to result from the same shear nomenon with closer or wider spacing betw

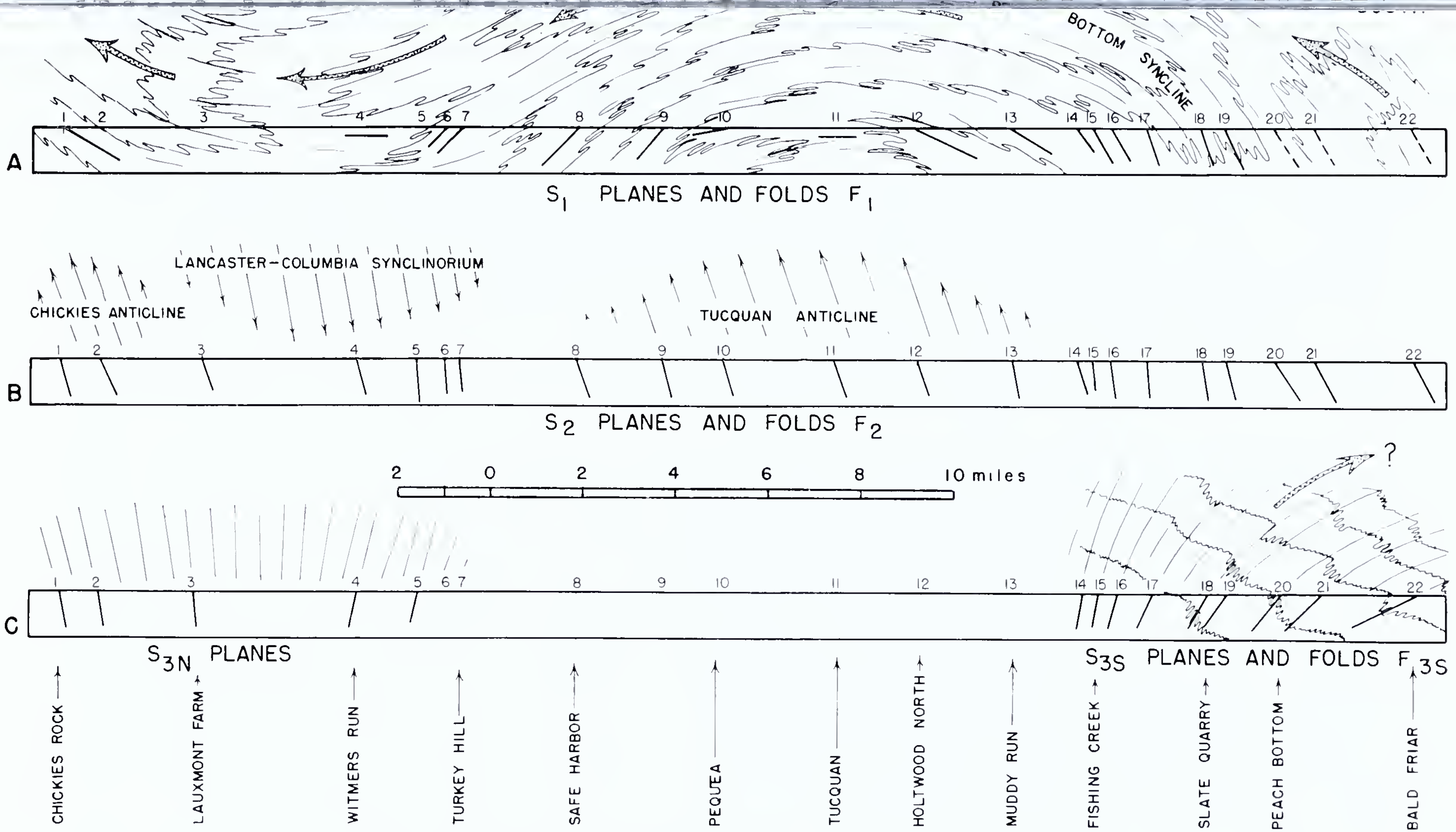

Figure 6. Diagram of dips of *S*-surfaces and axial planes along the Susquehanna River

planes dependent on lithology. There is danger in speaking of "the fracture cleavage" or "the flow cleavage" of a region.

Nevertheless, the general character of an S-surface seems to be dependent on metamorphic conditions and on the susceptibility of the micas to recrystallization. During D_1 all rocks suffered major flowage and metamorphism into schists, slates, metaquartzites, and marbles wherein S_1 represents the pervasive flow cleavage or schistosity. Almost all F_1 folds including some in the resistant quartzites, are isoclinal. The entire rock mass seems to have behaved as a great viscous body in which S_1 corresponds to the planes of laminar flowage.

In D_2 the mass appears to have been more rigid. Most of the deformation was by slip along microlithons with bending and only minor recrystallization of the micas along the slip planes. The degree of transition from flow to brittle yield in D_2 is a function of rock type. Most carbonates show evenly distributed flow cleavage, schists show minor flowage between the microlithons, and the quartzites have brittle fracture cleavage. D_3 is characterized by sharper fracturelike boundaries of the microlithons in the limestones and schists and by wider-spaced fracture cleavage transitional into jointing in the quartzites. D_4 appears only in the weaker schists and carbonates as widely spaced zones of combined folding, fracturing, and jointing.

This change in rock behavior from oldest to youngest deformations suggests a time sequence from: (1) viscous to brittle behavior; (2) almost complete recrystallization to no recrystallization; (3) movement on extremely closely spaced planes to movement on widely spaced planes; and (4) pervasive isoclinal folding to limited gentle flexing. The evidence is strong that all recorded deformations in the lower Susquehanna region have decreased in intensity and metamorphic effects with time.

Age of Deformations

The several deformations are closely related to the developmental history of the Appalachian geosyncline. All must be younger than the Ordovician Conestoga Limestone that they deform. The multiple S-surfaces produced cannot be part of one great deformation involving a single complex stress system because all unequivocable field age relationships show the same sequential development, the patterns vary independently of each other across the region, and the rocks and folds have distinctive behavior in each deformation in a sequence th implies waning stress conditions. The distin tive style of each deformation implies, but do not prove, time for decrease in the level metamorphic intensity between the successi deformations.

The ages of D_1 and possibly of D_2 can be o tained by radioactive methods from the ass ciated micas. Preliminary K-A age dat (Lapham and Bassett, 1964) from the low Susquehanna region set the major metamorp event at 320–330 m. y. These late Devonian early Mississippian ages probably reflect t regional recrystallization associated with Scarcity of younger age dates may mean t D_2 occurred so soon after D_1 as to be insepara by radiometric methods. On the other ha D_2 may have been much younger with sufficient associated recrystallization to sign cantly alter the ages in the dated rocks. purely structural grounds a late Paleozoic seems more likely for D_2. The far-reachi uniformly oriented S_2 surfaces are related the basement deformation of the region. T basement uplift of the Reading Prong and parallel Folded Appalachians seem to be as ciated with this orientation and style of formation. Thus, an age that is younger t the Pennsylvanian coal measures involved the Appalachian folding is indicated. At pres the entire problem of age of S-surfaces aw additional field and laboratory work. One of key problems is the relationship of D_1 and northward across the Great Valley into Folded Appalachians.

CONCLUSIONS

Our major conclusions are:

(1) Two major deformations, a third in mediate deformation, and a final minor formation may be traced as independe variable, superimposed fabrics across the lo Susquehanna region.

(2) The F_1 recumbent fold pattern horizontal fold axes in the north is traceable 30 miles southward into a zone of steep a planes with fold axes plunging directly d the dip. This is interpreted as part of a si flowage pattern from gneissic and schistose r in the southeastern Piedmont northwestw to the carbonate nappe structures of the G Valley, a pattern resembling that of Pennine Nappes. Persistence of the flow pat does not imply a similar distance of tect transport.

(3) The deformation that developed

ated, at least in part, to basement deforma-
n in the Mine Ridge anticline. It maintains
irly constant strike and steep dip across the
ryland and Pennsylvania Piedmont suggest-
a deep-seated regional origin.

4) Steeply dipping "roots" and horizontal
remities of F_1 and D_{3S} suggest that gravity
yed an increasingly important role near their
umbent terminations. The constant dip of
basement-related S_2 is in sharp contrast to
fanning dips of S_1 and S_{3S}. This feature of
parent roots to *S*-surfaces across a region may
one criterion for separating deeper seated
m more surficial parts of a deformation.

5) All these fold patterns may be traced
changed across the problematic Martic Line.
is strongly supports Cloos' original con-
sion that the Martic contact, whatever its
gin, is older than the fold systems.

(6) Although one structural pattern charac-
izes most of a given set of *S*-surfaces, con-
erable variation may occur with changes in
hology, metamorphic rank, and intensity of
formation. For example, S_2 is dominantly a slip cleavage or a slip folding, but in metamorphosed pelites it is a slaty cleavage; in quartzite it is a fracture cleavage; and in the carbonates it may consist of planes of flow folding. The parallel orientations and gradations into each other indicate that the same stress field may be responsible for quite diverse types of planar structures and cleavages.

(8) The sequence of structures in any given lithology indicates a progression from more mobile behavior in the earlier intense deformation to more brittle in the later, weaker deformations. The relative mobility of the rock seems to determine the type of cleavage and folding that results.

(9) The fabric of almost any outcrop in the area is triclinic resulting from superpositions of several essentially monoclinic fabrics.

(10) The method of plotting all structural data including age distinctions at a limited number of selected outcrops seems to be an effective technique for correlating structures in areas of multiple deformation.

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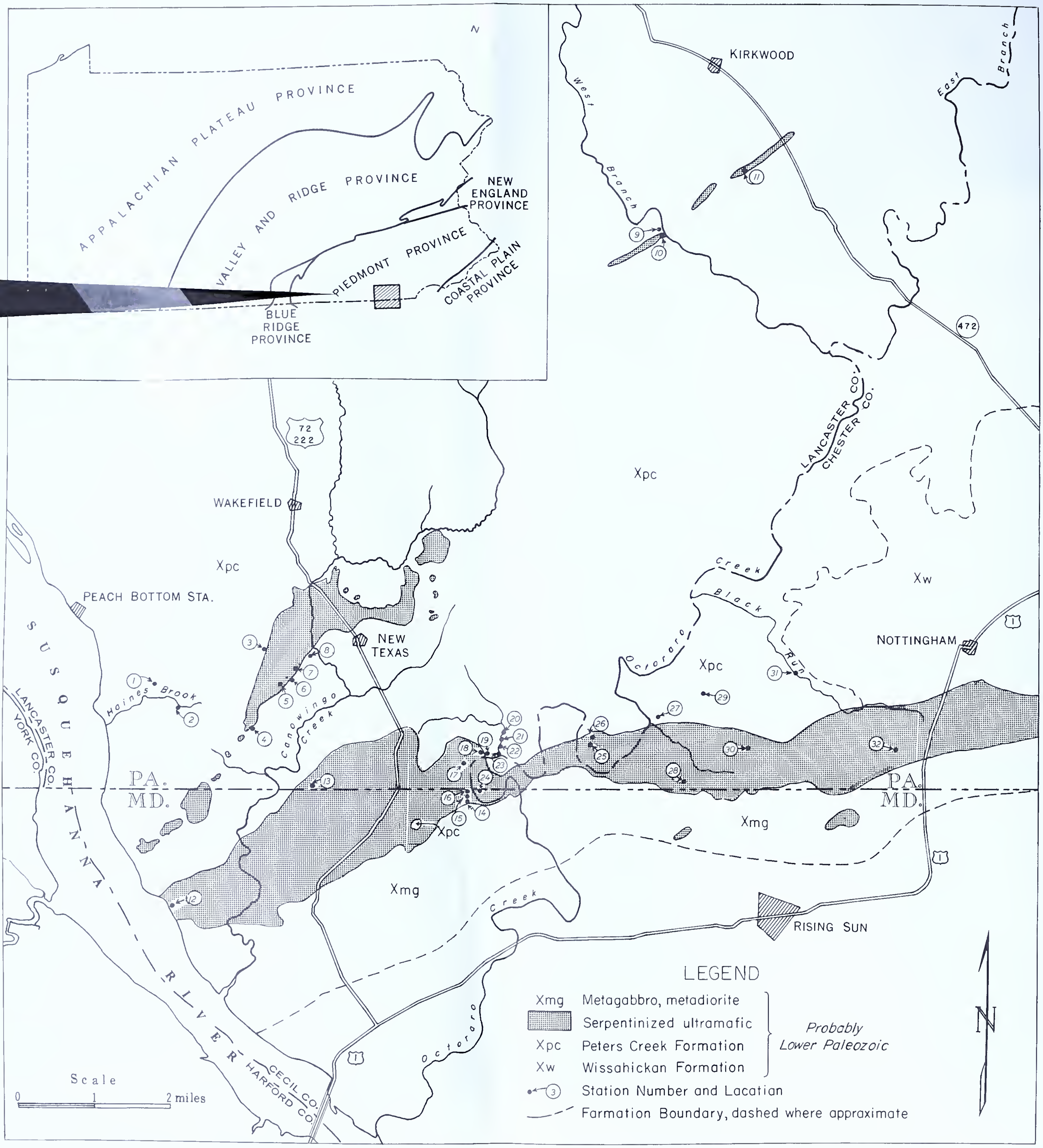

LOCATION AND GEOLOGIC MAPS, SOUTHEASTERN PENNSYLVANIA

AVIS M. LAPHAM *Pennsylvania Geological Survey, Harrisburg, Pa.*
LAWRENCE McKAGUE *College of Mineral Industries, Pennsylvania State University, University Park, Pa.*

tructural Patterns Associated with the erpentinites of Southeastern Pennsylvania

stract: In the Piedmont province of southern
ncaster County, Pennsylvania, equal area, lower
nisphere plots of lineations, and poles to folia-
ns and fractures are compared for serpentinite,
as at the schist-serpentinite contact, and schist.
alysis of the resultant patterns indicates that:
ar and strike joints are more numerous in
pentinite than in schist; fractures in the ser-
ntinite are more abundant and more varied than
schist; schist-serpentinite contacts are commonly
ared; near these contacts fracture planes and
nging fold axes tend to be steepened or over-
ned to the north; cleavage in schist near serpen-
ite parallels irregularities in the strike of the
pentinite contact; the major, southeastern ser-
ntinite belt transects the strike of regional
avage in schist at a small angle; and several de-
mations have affected both schist and serpen-
ite.

An analysis of the sequential age relationships of serpentinite fractures indicates that two deformational patterns are present that are younger than the final emplacement of the serpentinite.

From a discussion of the patterns, it is concluded that: fracture pattern analysis of serpentinites and the surrounding host rock can be utilized in a study of serpentinite tectonics; based upon differences in homogeneity and anisotropy between schist and serpentinite, serpentinites responded to deformational stresses largely as a brittle material; the serpentinite was more responsive than the schist to local stress variations; the final emplacement of the serpentinite was controlled by some pre-existing structural lineament; the superimposed fracture patterns were locally influenced by the south-dipping attitude of the schist-serpentinite contact; and chrysotile veinlets, banded chromite, pegmatites, and deweylite-filled fractures exhibit preferred orientations.

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eological Society of America Bulletin, v. 75, p. 639–660, 13 figs., 1 pl., July 1964

INTRODUCTION

The structural history of serpentinized ultramafic rocks of the Alpine type is complex, largely because the ultramafic rocks are situated in eugeosynclinal belts that commonly have been subjected to multiple deformation. The mode, or modes, of emplacement have been obscured by intense shearing, and by processes, such as serpentinization and steatitization. A seemingly infinite variety and abundance of fracture surfaces have fostered the impression that unravelling their significance would be too complex to warrant the effort. The authors believe that quantitative analysis of the serpentinites of southeastern Pennsylvania will aid in understanding the origin of these intrusions, the regional deformations with which they have been involved, and the character of their response to deformational stresses. In addition the analysis of fracture surface pole plots may prove useful to other workers engaged in research on Alpine-type ultramafic rocks.

Throughout this report the authors have used the term "serpentinite" as an abbreviation of "serpentinized ultramafic" as proposed by Lodocnikow (1936, p. 27, 78).

The area under consideration (Pl. 1) lies in southern Lancaster and Chester counties, Pennsylvania, and in northern Cecil County, Maryland, along the northwestern boundary of the Piedmont core of the Appalachian geosyncline. The Martic Line, a major structural feature of the Piedmont which separates schists from metamorphosed carbonate rocks, lies 16 miles north of the serpentinites. The Piedmont in this area is composed of the Glenarm Series of metamorphic units into which the ultramafic rocks have been intruded. The Glenarm Series has been subdivided (Knopf and Jonas, 1923; Bascom and Stose, 1932) into the Peach Bottom Slate, Cardiff Conglomerate, Peters Creek Formation, Wissahickon Formation, Cockeysville Marble, and Setters Formation. The Cardiff Conglomerate, Cockeysville Marble, and Setters Formation are not present in this area. The Peters Creek Formation forms the north contact of the southern serpentinite and completely envelops the northern serpentinite belt (Pl. 1). Northward from the northern serpentinite to the Peach Bottom Slate, the Peters Creek Formation is composed of two distinct interbedded lithologies, a mica schist and a relatively pure, generally thin-bedded quartzite. South of the northern serpentinite, between the two serpentinite belts, the char ter of the Peters Creek Formation chan markedly, containing much less mica schi and only a few pure quartzite lenses. T dominant rock type is a metagraywacke co taining feldspar, chlorite, quartz, and mi amounts of epidote, garnet, and mica. Th quartz-epidote units are common and m represent metamorphosed volcanic rocks. No of these individual lithologies has yet be mapped as a separate unit. A complex area metagabbro, granodiorite, and granite gne occurs immediately south of the serpentinit

The Glenarm Series is folded into a syncli in the center of which is the Peach Bott Slate, flanked by the Peters Creek and W sahickon schists successively. Recent work McKinstry (1961) and Freedman and oth (1964) in these units has shown that more co plex structures exist and are the result of seve successive deformations. A summary of th results, especially those of Freedman and oth (1964), is especially pertinent since structu patterns within the serpentinite will be refer to those patterns which they have observed the schists. Briefly, Freedman and others (19 recognize three independent deformations (D D_2; D_3) within the Glenarm Series, which va in character and extent of development fr north to south. To the south, in the area of t serpentinites, the axial planes of the two earli deformations recognized by Freedman a others (1964) are indistinguishable, both str ing about N. 50° E. and dipping about 60° S These deformations are characterized by clos spaced flow cleavage, structural lineations, m recrystallization within the cleavage plane, a folds of greater amplitude than those whi resulted from the succeeding deformation (D This latter deformation (D_3) is characteriz by axial planes that strike about N. 80° E., a dip about 40° NW., and by cleavage that often widely spaced with no significant m recrystallization. The conclusion drawn is th D_3 resulted in fracturing without the extensi flowage and recrystallization characteristic the earlier deformations. A similar set of pa terns, which until now have only been assum to be present (Weiss, 1949, p. 1722), ex within the serpentinites.

One additional structural anomaly has be noted previously by many workers in the ar Approximately at the Pennsylvania-Maryla state line, the two serpentinite belts dive northeastward, the larger and more southe belt becoming nearly east-west in strike, cro the dominant regional strike at a small acute le (Pl. 1). Recognition of this structural ure is important to an understanding of the e of emplacement of the serpentinite.

he age of the Glenarm Series, although the ject of much discussion, is generally con- red to be early Paleozoic. McKinstry 51, p. 561) prefers an Ordovician age, at t in part. Mica and feldspar K-Ar and Zir- U-Pb age dating have revealed several eozoic deformations, two throughout the palachian belt, about 450 m.y. and 350 ., and a third recognized in the southern palachians (Kulp and Eckelmann, 1961, p.) about 250 m.y. Recent K-Ar dating in nsylvania (Lapham and Bassett, 1964) indi- es that the last mica recrystallization (D_1 /or D_2) occurred at about 335 m.y. ± 5 cent, and that the ultramafic intrusion is at t 455 m.y. old.

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CHNIQUES

The structural interpretations in this report based on lower hemisphere Schmidt net ts of lineations and of poles to planar sur- es. In the schists surrounding serpentinite, avage (flow and fracture), joints (*ac*, *bc*, ique), axial planes, and fold axes were asured and plotted separately. Although 100 es is considered a minimum number for urate representation, in actual practice this mber usually could not be measured because schist outcrops are small, widely scattered, d often show evidence of slumping.

In serpentinite all fracture surfaces were tted as joints except where there was clear dence of faulting, definite foliations, or rysotile lineations. These "joints" are widely spaced fractures that vary in separation from several inches to several feet. The majority are slickensided, although the displacement is often small or of indeterminate extent. In a few areas, especially in the north serpentinite belt, closely spaced fractures, about 1 cm apart, were interpreted as a possible cleavage, and plotted separately. Where the outcrops are large and also in the few available quarries such as west of New Texas (Pl. 1, locs. 5, 7), areas about ten feet wide were blocked out and all the surfaces within that area measured before moving to another ten foot block nearby. In order to evaluate repeatability, several stations were remeasured varying the total number of poles measured from 100 to 300. In each case, after contouring, the plots exhibited the same characteristics. However, other possible sources of error should be mentioned. One of the most important of these is bias by the observer who may "see" more of one fracture orientation than another. At several localities, in order to reduce this error to a minimum, the recorder exchanged position with the observer and remeasured the same area. No significant variations were observed. The strike of the outcrop or quarry face also tends to introduce an error because planes nearly perpendicular to the face could be measured with greater frequency. Two other errors are peculiar to fracture measurements in serpentinite. One is the presence of numerous curved surfaces, which were measured only when they clearly belonged to two intersecting surfaces, and the other is the presence of magnetite, which affects compass readings. However, these possible sources of error can be compensated for in the field.

Fold axes were measured directly from small folds rather than from lineations on folds.

It was necessary to contour the serpentinite diagrams to reveal any consistent pattern. In general, a concentration of less than 3 per cent is probably not significant. More than 600 surfaces were measured in schist, and over 3400 in serpentinite at the localities listed in Table 1.

Designation of surfaces by the letter "*S*" with numbered subscripts to denote the relative ages of the surfaces follows the relationships determined by Freedman and others (1964) and the present authors for stations in the schist. For example, S_0 represents bedding, S_1 the earliest cleavage, S_2 the next youngest cleavage, *etc.* Similarly a fold associated with an S_1 cleavage is designated F_1, the deformation D_1, and the fold axis A_1. Throughout the report explanation of serpentinite fractures is sought in terms of the known regional patterns. The validity of assigning these designations to concentrations on serpentinite plots is established by the consistency with which surfaces of similar orientation are present in serpentinite, and by the few surfaces in serpentinite from which age relationships could be determined.

strike from their Haines Brook station. addition, a few *ac* joints were noted, but oblique joints.

At the two Haines Brook stations the m competent and brittle, impure quartzite (Pl loc. 2) has preserved the S_1–S_2 orientatic whereas S_3 dominates in the less compete less homogeneous mica schist (Pl. 1, loc. 1)

Table 1. Location of Structure Measurement Stations

Map position	Location	Rock type
1	Haines Brook	Quartz-mica schist
2	Haines Brook	Metagraywacke or impure quartz schist
3	Pleasant Grove Church	Magnetite-talc-mica schist
4	Black Baron	Chlorite schist
5	West of New Texas	Serpentinite
6	West of New Texas	Chlorite-quartz-mica schist
7	West of New Texas	Serpentinite
8	Conowingo Creek	Metagraywacke or quartz schist
9	White Rock	Quartz-mica schist
10	White Rock quarry	Serpentinite
11	Burkholder quarry	Serpentinite
12	Susquehanna River	Serpentinite
13	Line Pit	Serpentinite
14–16, 24	South Cedar Hill quarry	Serpentinite
17	Cedar Hill quarry	Serpentinite
18	North Cedar Hill quarry	Serpentinite
19–23	East of Cedar Hill quarry	Quartz-mica schist
25–26	Wood mine	Serpentinite
27	West of Lees Mills	Quartz-mica schist
28	Goat Hill magnesite mine	Serpentinite
29	North of Lees Mills	Quartz-mica schist
30	Southeast of Lees Mills	Serpentinite
31	Black Run	Quartzitic schis
32	Rhodewalt quarry	Serpentinite

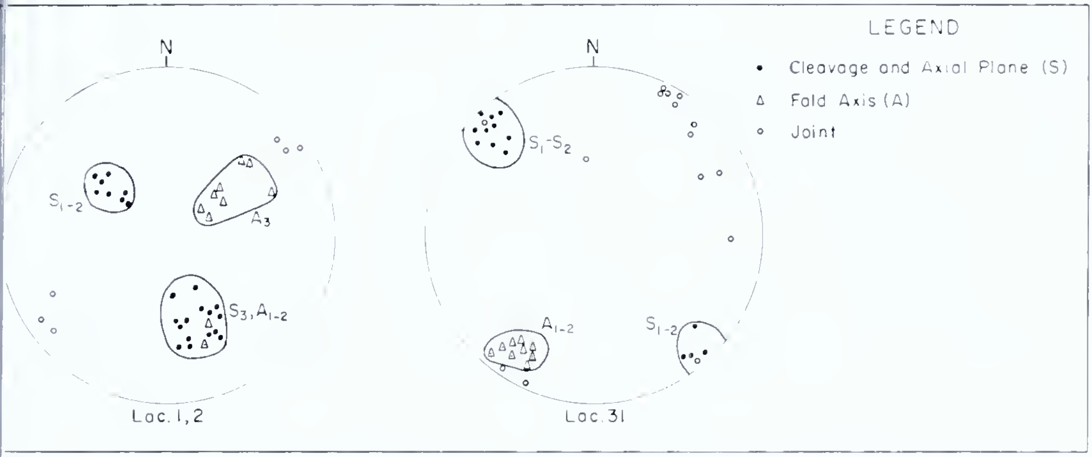
STRUCTURAL PATTERNS IN THE GLENARM SERIES

Regional Patterns

North of the area under consideration, Freedman and others (1964) recognize an S_1 and an S_2 flow cleavage. The S_2 cleavage remains constant in orientation from north to south, whereas S_1 changes gradually from a northwest dip to a southeast dip toward the south. In the Peters Creek Formation near the serpentinites, an S_3 fracture cleavage dominates, especially in the less competent, more micaceous units. At Haines Brook where it enters the Susquehanna River, Freedman and others note an undifferentiated S_1–S_2 cleavage striking N. 50° E. and dipping about 60° SE., and an S_3 cleavage striking about N. 80° E. and dipping about 40° NW. A similar pattern is illustrated in locations 1 and 2 of Figure 1, for measurements taken about 1000 feet to the east along is reasonable to expect that the less compet units would reflect the youngest deformat more strongly. In part, this may explain t apparent absence of an S_3 cleavage in quartzi schist at location 31 several miles east of Hai Brook. Other factors, such as a variation alc strike or the presence of the serpentinite co tact nearly a mile to the south, may contrib to a deviation from the Haines Brook patte At location 31 there is also a predominance extensional over shear jointing, and a steep ing of the undifferentiated S_1–S_2 cleavage (F 1).

Along the Susquehanna River from C lumbia, Pennsylvania to the Maryland st line, extensional (*ac*) joints appear to predo inate over *bc* and oblique joints, although t joints have not been studied in a quantitati manner. Similarly, Cloos (1937, p. 74–76) a Weiss (1949, p. 1722) note that such cr joints predominate in the Pennsylvania-Ma

Piedmont. The authors believe that the joints, the characteristic orientations of $_2$ and S_3 cleavages, and their observed age onships, define the patterns both of typi- hist outcrops and of central portions of the ntinites. These patterns are in contrast to what different, but related, patterns near ntinite contacts.



ure 1. Structural elements in the Peters Creek Formation with poles plotted on an equal area net, llustrating normal schist patterns. Sequential “*S*” surface and fold axis (“*A*”) designations are xplained in text. Location numbers refer to stations in Plate 1.

rns in the Glenarm Series near Serpentinite

the southwest, where the serpentinites erge and within a few feet of the serpentin- ontract, chloritization, steatitization, silici- ion, and intense shearing are evident (Pl. cs. 6, 19). This alteration, which is reflected ariations in the structural pattern from of typical schist, is illustrated in three s near the contact (Figs. 2–4).

ive stations that lie approximately in a h-south line approaching the serpentinite act north of Cedar Hill quarry are shown igure 2. The most striking and consistent ation is the change in strike, steepening of plunge, and finally overturning of the ige of the fold axis to the north (A_1–A_2) as serpentinite is approached. The S_1–S_2 cleav- also varies but in a less consistent manner implies a possible warping of their associ- l axial planes near the serpentinite. Al- igh the angle between the pole to the axial ie and the fold axis will ordinarily be 90°, ie axial plane is warped, the fold axis will ear to deviate from a 90° relationship. Near entinite (Fig. 2, locs. 19–23) this deviation is as much as 12°. However, because of point scatter, these deviations should be considered as no more than a suggestion that axial plane warping may be present. Other observations of interest (Fig. 2) are the general parallelism of the S_1–S_2 cleavage and the serpentinite contact at location 19 which is nearly north–south, and the predominance of oblique joints over *ac* joints.

Somewhat similar relationships are observed as the serpentinite is approached in the Lees Mills area (Fig. 3). A less extensive fold axis shift is present. Although no outcrop is sufficiently close to the contact to measure any actual north plunge that might be present, the change in plunge of the axis as the serpentinite is approached suggests a steepening to the north. There is again less consistency in the variation of the S_1–S_2 cleavage, although the scatter increases noticeably near the serpentinite. Here also (Fig. 3, locs. 27, 29, 31) the plotted maximum angle between the fold axis and the average attitude of the axial plane deviates from 90° by as much as 10°, suggesting the presence of warped axial planes near the contact. The cleavage scatter probably reflects a tendency toward parallelism of the schist with the serpentinite contact which is nearly east–west (Fig. 3). Oblique and questionable *ac* joints are noticeable at location 27, nearest the contact. No S_3 orientation was discerned in this area.

The third example of contact relationships (Fig. 4) is shown in a series of stations along the north contact (Fig. 4, locs. 3, 9) and south contact (Fig. 4, locs. 4, 6, 8) of the northern serpentinite belt. Although there is an insufficient number of outcrops to chart a structural variation as the contact is approached, the diagrams along the contact do illustrate the anomalous patterns found at the contact. Location 1, 2 (Fig. 4) at Haines Brook is presented for comparison as typical of the schist pattern. A general steepening of cleavage and axial planes near the contact, the predominance of oblique over *ac* joints (identified by their attitude relative to S_{1-2} and S_3 poles), and a tendency toward a parallelism between the S_1–S_2 cleavage and the intrusive contact are well illustrated. Shearing along the contact can be seen in the field at location 6 (Fig. 4). A change in orientation of these planes from the schist toward the center of the serpentinites (south to north) is shown by the arrow (Fig. 4, loc. 6). This gradual reorientation away from the contact suggests that shearing has rotated previously formed planes. The anomalous concentration of points at location 8 (Fig. strongly suggests a fault, especially since t rather resistant metagraywacke forms a to graphic high striking nearly perpendicular the serpentinite contact. Cleavages charact istic of S_1–S_2 and S_3 orientations are either c placed or obliterated here.

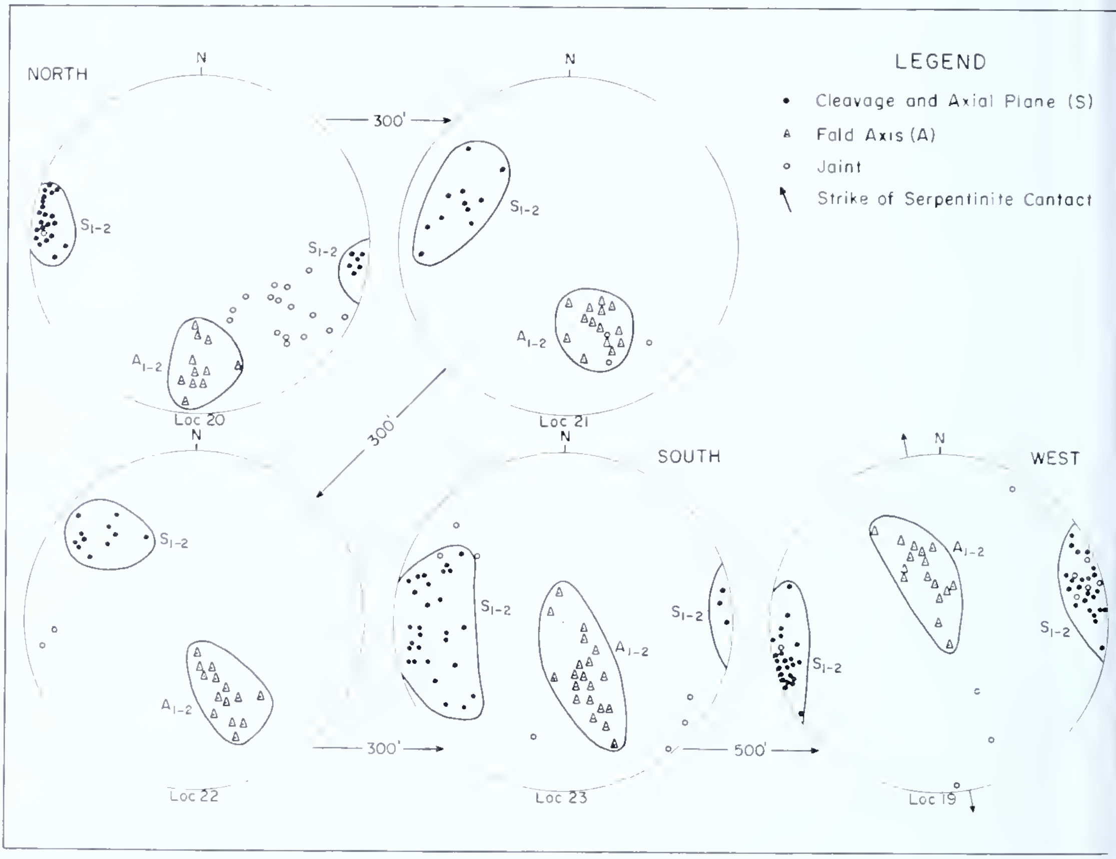


Figure 2. Structural elements in the Peters Creek Formation approaching the serpentinite in t southern belt in a line from north to south to west, north of Cedar Hill, Pennsylvania, illustrati anomalies characteristic of the contact

In summary, characteristic structural tures in the country rock schists near serpentinite contact are:

(1) parallelism of the dominant clea (probably S_1–S_2 in most cases) and the a planes of folds to the strike of the serpenti contact, even where the contact is 90° to regional strike;

(2) at several locations a steepening of axes and/or cleavage toward the contact;

(3) an increase in oblique joints (shear) r tive to the *ac* (extensional) joints which dominate farther from the contact;

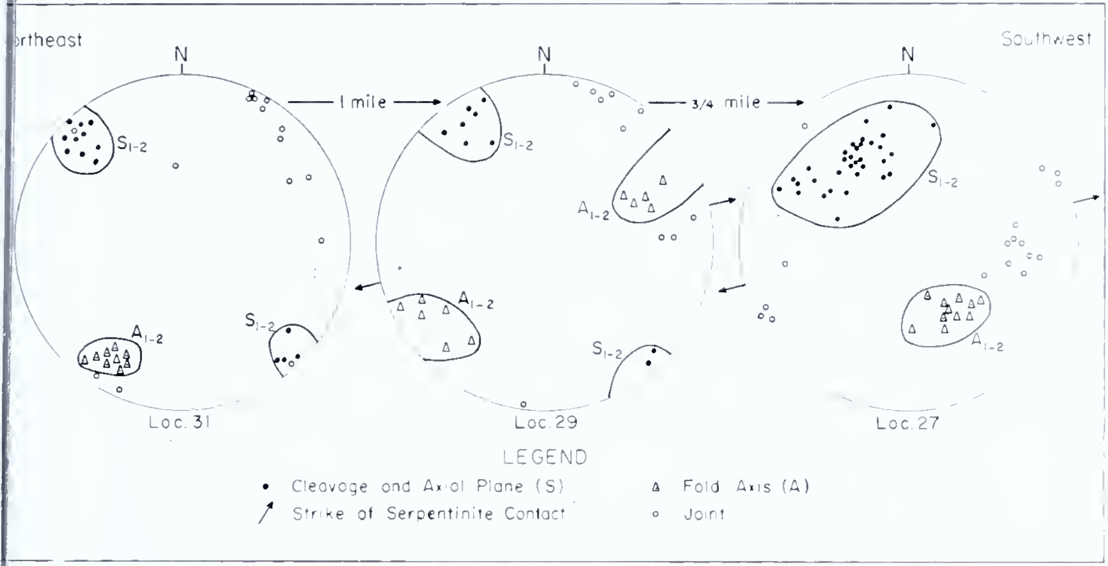
(4) shearing and faulting along the cont which may have rotated pre-existing pla

ing to obliterate or reorient earlier cleav- and which may have resulted in the ation of oblique joints.

UCTURAL PATTERNS ERPENTINITE

ral Characteristics

he fracture surfaces in serpentinite are numerous and complex than in the schist, when plotted, these serpentinite fractures ilt in a wider scatter of pole maxima than poles in schist. An observable difference exists in the response of the narrower and re fragmented northern serpentinite belt ative to the more extensive southern belt. r example, the extent of fracturing increases the size of the serpentinite mass decreases, observation that has been noted previously abrielse, 1960; Noble and Taylor, 1960; and hers). Finally, evidence for late or repeated vement on earlier fractures is indicated by ferent directions of offset and slickensiding the same set of fracture systems, some of ich have been disturbed by later dike in- sions.



gure 3. Structural elements in the Peters Creek Formation approaching the serpentinite contact in the southern serpentinite from the northeast to the southwest near Lees Mills, Pennsylvania, illustrating anomalies characteristic of the contact

mary(?) Structures

The existence of primary structures in an pine-type ultramafic pluton such as this is ghly debatable, but consistent orientations of certain features suggest the possibility. One of these is the disseminated, banded chromite that occurs near the north contact of the southern serpentinite belt and is parallel to this contact (Fig. 5). The area from which the pole plots in Figure 5 were measured is north of location 17 (Pl. 1). Here the strike of the contact changes from northeast to northwest, and this is reflected in the partial girdle for chromite illustrated on the Schmidt net. The concentration of banded chromite near the north contact and its absence in any significant quantity near the south contact is characteristic and may represent a primary, gravity-controlled differentiation that has not been greatly disturbed by later deformation.

In the center of Cedar Hill quarry (Pl. 1, loc. 17) faint, dark, nearly vertical bands strike parallel to the north contact. In thin section these bands are parallel trails of grains of magnetite "dusting" or "exsolution" and may represent an original variation in iron content from a more iron-rich olivine or an iron-bearing pyroxene.

Fracture Orientations from the Center of the Southern Serpentinite

Representative examples of the serpentinite deformational pattern are more likely to be present near the center of the larger, southern serpentinite belt (Fig. 6) than in the contact zones or within the smaller, northern serpentinite belt. The authors believe these representative examples are characteristic of the serpentinite deformational pattern as a whole.

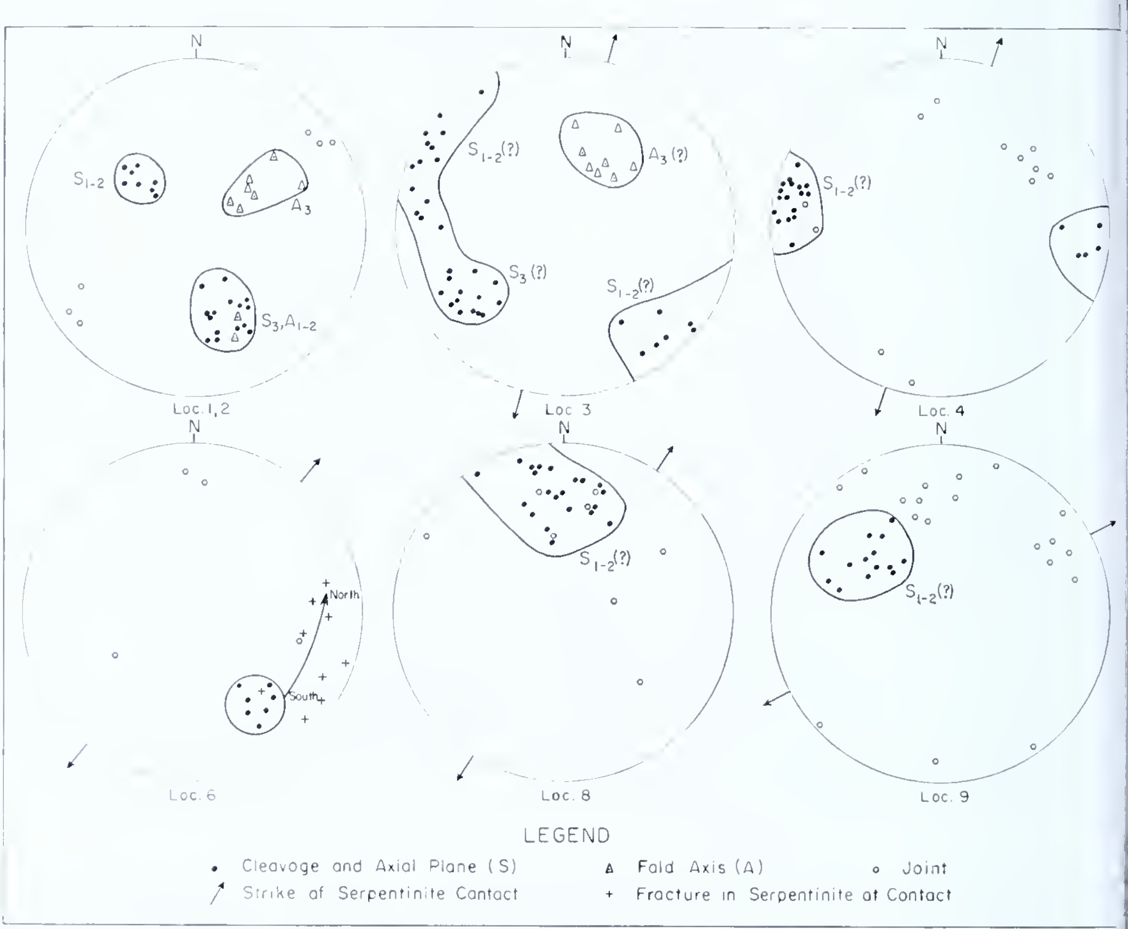


Figure 4. Structural elements in the Peters Creek Formation at contacts along the northern se pentinite belt illustrating anomalous patterns at the contact

In a general way, the patterns are quite similar, exhibiting persistent maxima with similar orientations. All four diagrams (Fig. 6) show a concentration in the northwest quadrant from planes striking northeast and dipping at a moderately steep angle (about 60°) to the southeast. This is the position of the S_1–S_2 cleavage maximum observed in typical schist. It is present in every serpentinite outcrop studied in this area. Similarly, there is a weak concentration of poles in the southeast quadrant of the net analogous to the S_3 position in the schist, representing planes striking east northeast and dipping northwest. In three of the four nets, there is a strong concentration (northeast quadrant) of poles to planes striking northwest and dipping steeply southwest which are interpreted as extensional joints (*ac*) and whi exhibit a sufficiently wide scatter to belong either or both of the F_1–F_2 or F_3 fold syste The gently northwest dipping planes at lo tions 17 and 32 (Fig. 6), which are fractu filled with deweylite, are discussed lat Oblique joint planes (shear directions) a weakly expressed (Fig. 6, loc. 17) or abse The majority of planes dip south, the o significant exception being a concentration the S_3 position. In general, these maxima do appear to shift significantly as the strike of t serpentinite contact shifts, with the possil exception of a nearly vertical cross joint (tensional) striking approximately north–sou at location 32 (Fig. 6).

Some variation appears to exist from west east, although it may be more apparent th real. To the east a maximum at the S_3 positi is more noticeable. As noted above, pla corresponding to an orientation of extensio

n (*ac*) may be shifting to a more north–
1 strike as the serpentinite contact trends
: east–west. At the extreme southwest of
rea at the Susquehanna River the pattern
omalous and may be the result of rotation.
ith the exception of location 12, summary
ams for all serpentinite stations for the
nern serpentinite belt are illustrated in
re 7. An arbitrary division was made be-
n a western (locs. 12–25) and an eastern

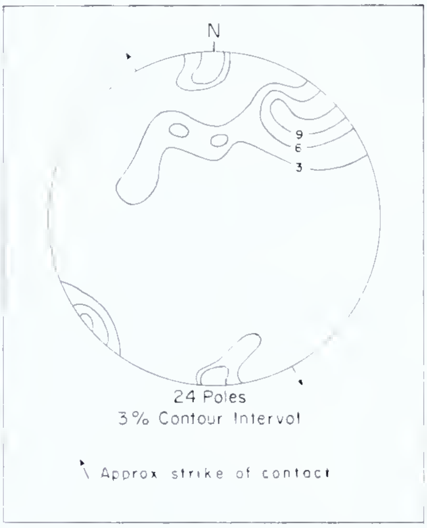


Figure 5. Primary(?) banded chromite and magnetite parallel to irregular serpentinite contact, north of location 17, an equal area pole plot

p (locs. 28–32). The diagrams also include
ons near the contact, which are discussed
. The following characteristics of the south-
serpentinite belt, which have been noted
iously, are more clearly in evidence from
e summary diagrams: a consistent maxi-
n at the S_1–S_2 position in the northwest
drant; a weak, but consistent, maximum
ie S_3 position in the southwest quadrant; a
lominance of joints interpreted as exten-
al (northeast quadrant) over oblique joints
rpreted as shears at an acute angle to them;
jority of south-dipping planes that conform
ie direction of dip of the serpentinite. The
significant difference between the west
east diagrams is the presence in the west
ram of a set of planes striking N. 40° W.
dipping 70° NE. These planes are found
at the north serpentinite contact.

he presence of persistent fracture maxima
erpentinite at cleavage orientations found
in the surrounding schist is interpreted as evidence that the same deformations that have affected the schist have also affected the serpentinites.

Fracture Orientations at Serpentinite Contacts

The serpentinite contact is characterized by a dense, nontextured serpentine containing no relict olivine. This type of serpentine in which all the relict mesh texture has been destroyed is also characteristic along faults and dikes. Thus it seems probable that its presence at the contacts represents differential movement between schist and serpentinite.

Examples of fracture orientations at the contact of the southern serpentinite belt are presented in Figure 8. Nets for locations 18 and 14 are typical of anomalous contact patterns, whereas the pattern for location 26, although it is within 100 feet of the contact, is more typical of patterns from the center of the serpentinite. Such variation suggests that contact fracture patterns vary locally.

At locations 18 and 26 (Fig. 8), northwest-striking joints are dominant, but the net for location 18 illustrates a north dip similar to that found in schist near the contact. With respect to the regional strike, these surfaces (Fig. 8, loc. 18) lie in the *ac* plane, but with respect to the strike of the contact and the locally conformable schists they are parallel to the strike (*bc*). This results from the irregularity of the contact at location 18 (Pl. 1). Weakly developed oblique planes also appear to have developed. The net for location 14 illustrates the conformity of joints with the east–west strike of the contact, which is not the case nearer the center of the serpentinite (Fig. 6). It should be noted that planes parallel to the strike with an orientation of an S_1–S_2 cleavage in the schist are not present. The double maximum at location 14 represents curved planes easily visible in the field.

All of the fracture patterns for serpentinite in the northern belt (Fig. 9) are from data near the contact. Because of this fact and because these serpentinites are small (and therefore relatively more mobile under deformational stresses than the serpentinite of the southern belt), these nets are more representative of contact relationships.

The maximum concentration of poles to planes which strike about N. 80° E. and dip nearly vertically is present in each of the diagrams. In addition, a weak concentration is present in three of the four, striking about N.

80° E. and dipping about 45° NW., which may correspond to S_3. In terms of the strike of the serpentinite contact, the N. 80° E. planes would represent oblique shear directions at locations 5 and 7 (Fig. 9) where the strike of the contact is about N. 30° E., and either strike or oblique joints at locations 10 and 11 (Fig. 9) where the strike of the contact locally is about N. 80° E. However, because there are northeasterly striking planes (northwest quadrant) at the latter locations, shears are most likely present here in any case. Fractures that could be interpreted as extensional in terms of the regional strike are also present. However, oblique ("shear") joints and strike-slip joints predominate at least within 150 feet of the contact (Fig. 9, loc. 7).

With the exception of a stronger concentration of planes corresponding to the position of S_3 cleavage at location 11 at the northe
end of the belt, no consistent variation fr
southwest to northeast appears to exist in t
belt. As noted previously, the majority
planes dip rather steeply to the south. T
S_1–S_2 orientations of the schist are absent
only weakly present.

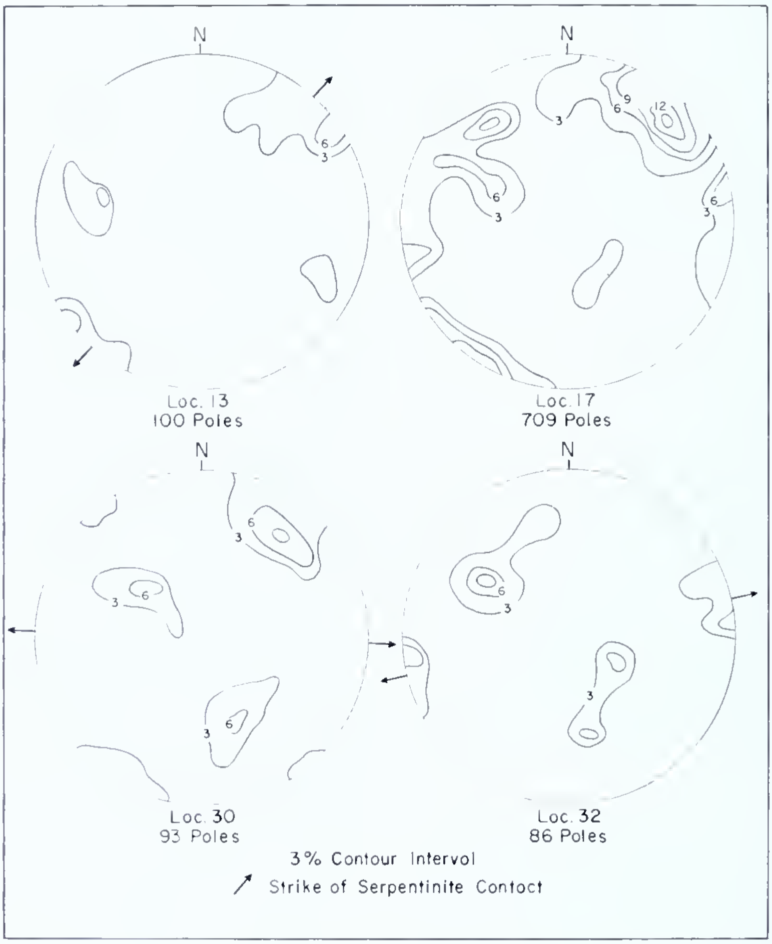


Figure 6. Equal area pole plot of fractures from localities near the center of the southern serpentinite, and from west (loc. 13) to east (loc. 32)

A summary of interpretations of the frac
pattern data near the contact, within ser
tinite, reveals: (1) a general parallelism of f
tures in the serpentinite to the strike of
contact and to cleavage in the schist at
contact; (2) a relatively greater numbe
oblique (shear?) planes than extensiona
contrasted with the dominance of extensi
planes toward the center of the serpenti
also an apparent increase in these oblique pl
within the smaller serpentinite bodies (jo
are not necessarily contemporaneous with cl

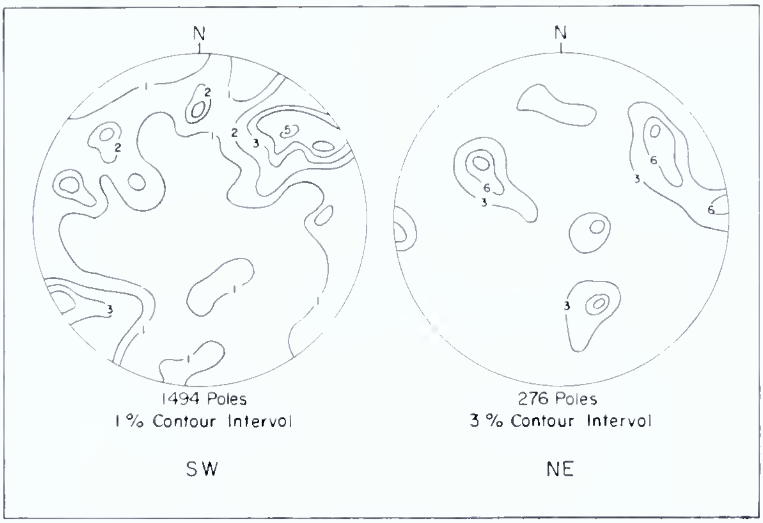


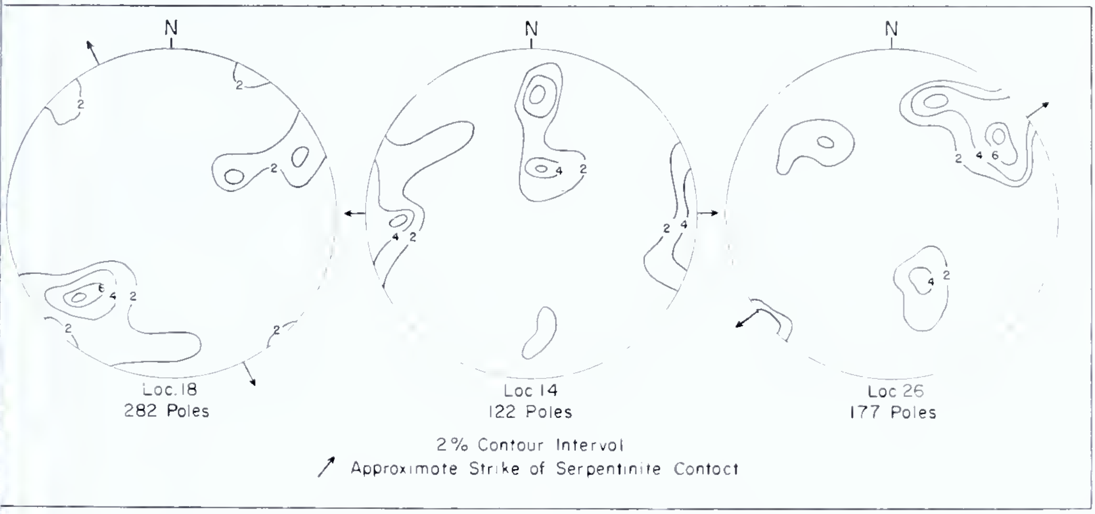
Figure 7. Summary of fractures from southwestern and northeastern areas of the southern serpentinite, excluding location 12

(3) a tendency toward obliteration of the ₂ orientation as a possible result of this ing; and (4) a steepening and northward ion of planes that are parallel to the strike e serpentinite.

ellaneous Orientations in Serpentinite

rtain minerals and structures in serpentin- xhibit well-defined orientations. Some do clarify the regional history, but they do some light on the minor details of ser- inite problems. Their very consistency in area is in itself significant.

racture cleavage" in serpentinite (Fig. as used in this report is defined as closely ed fracture surfaces varying in separation from a few tenths of an inch to several inches. The majority of these surfaces were measured in the northern serpentinite belt where they are better developed than in the southern belt because the northern belt is comprised of small, conformable lenses of serpentinite and reacted less competently. These planes, approximately parallel to the regional strike of the schist and the strike of the contact, are steeply dipping with a greater concentration dipping southeast. If, as the authors believe, these are analogous to the dominant cleavage in the adjacent schist, then the steepening of cleavage in contact schists is supported by these data from the serpentinites. Their angular scatter of about 60° could be the result of many factors such



gure 8. Fractures in the southern serpentinite belt at the north (locs. 18, 26) and south (loc. 14) contacts

as a combination of S_1–S_2 cleavage, rotation produced by shearing from later deformation, block reintrusion of serpentinite, or a combination of such factors. This "cleavage" is not distributed uniformly, but usually occurs in zones and is especially evident in areas of strong chloritization, steatitization, and vermiculitization. These zones are less competent than unaltered serpentinite and are younger than the major period of serpentinization. Therefore, this "cleavage" is younger than the serpentinization and the alteration.

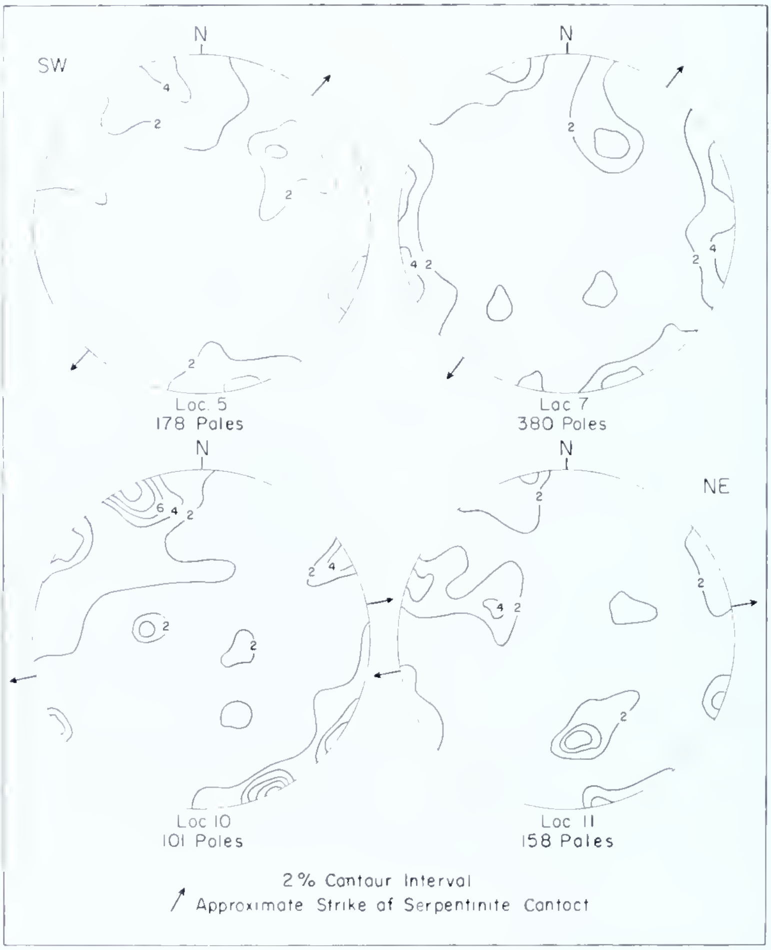
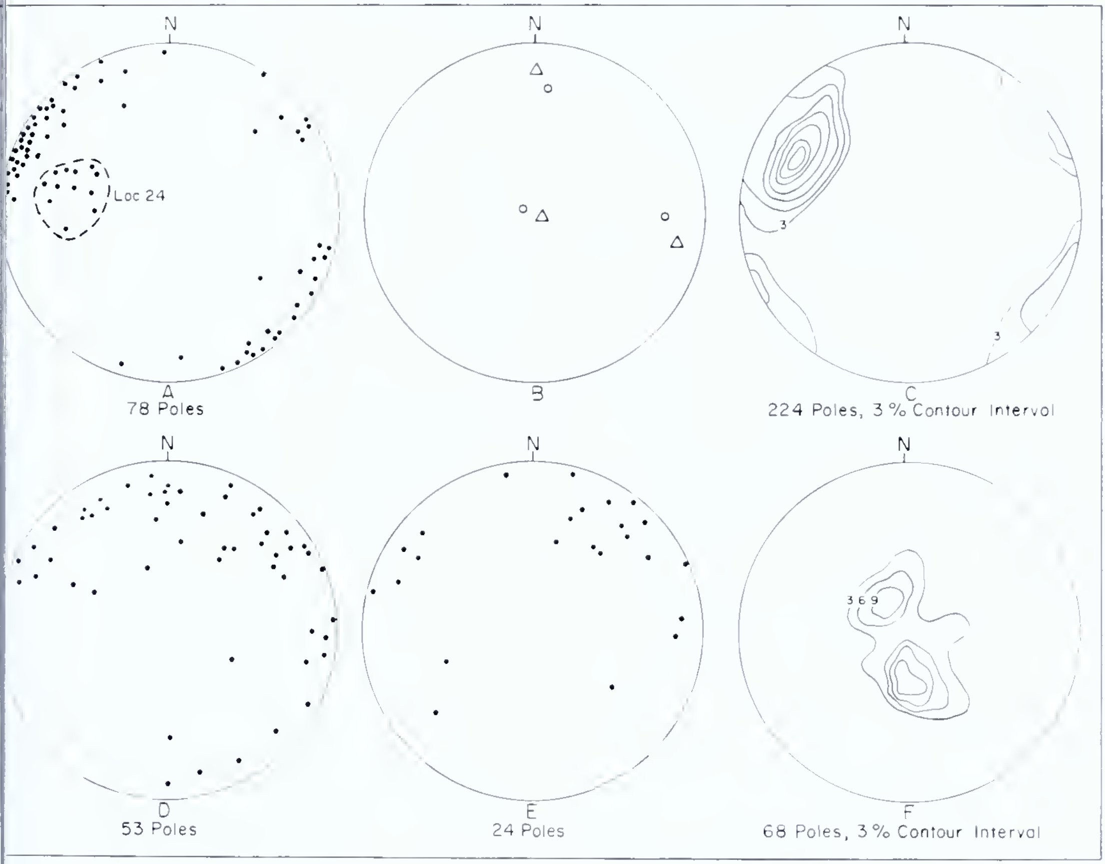


Figure 9. Fractures in the northern serpentinite belt at the contact

In several of the quarries, joint sets of a regular nature form rectangular blocks within the serpentinites. The two illustrated in Figure 10B are from localities 5 and 11 (Pl. 1). They are also present at locality 32 (Pl. 1) but could not be measured accurately. Of the three planes, the nearly horizontal one is the least uniform. The origin of these notable features is problematical. The two steeply dipping planes are bisected by the regional strike and n
represent conjugate shears. Similar joint
are common elsewhere in serpentinites and
senior author has seen them especially well
veloped at the Belvidere Mountain asbes
quarry at Eden Mills, Vermont.

The majority of cross-fiber chrysotile vein
(Fig. 10C) strike northeast and dip steepl
the southeast, paralleling the "fracture cl
age." A few are perpendicular to the regi
strike and are less well developed. The vei
range from a few mm to several cm in len
are quite narrow, and pinch out at both e
They have the appearance of extensional
fractures and developed late in the serpent
zation sequence after the formation of the
D_2 fractures. Subsequently they have b
deformed by a later period of shearing. Pe
graphic work strongly suggests that the chr
tile filled open fractures.

Major faults, dikes, and chlorite-vermic ature fillings exhibit preferred orientations . 10D, 10E), dipping south at steep angles are typical of the majority of surfaces in entinite. The steep dips of the fractures probably the paths most accessible to the nding solutions responsible for the pegitic dikes.



gure 10. Miscellaneous orientations in serpentinite: fracture cleavage (A); joint sets (B); chrysotile veinlets (C); major faults and dikes (D); chlorite-vermiculite fractures (E); deweylite fractures (F)

eweylite (Fig. 10F) fills nearly horizontal tures and, as might be expected from this ntation, is believed to be of secondary in (Lapham, 1961, p. 169–171). No relaship could be found between these nearly zontal planes and the existing topographic ace. Deweylite is also present in steeply ping, feather fractures that branch from the angle planes, and in moderately steep veins extend from the surface, becoming shaler with depth.

n conclusion, the authors would like to phasize that most of the orientations can be ibly related to a consistent deformational em or systems. The majority of the "fracture cleavage," chrysotile, veinlets, oblique joints, and dikes are foliated in planes consistent with these deformational patterns.

Summary of Structural Patterns in Serpentinite

Summary diagrams for fracture surfaces in the north and south serpentinite belts, exclusive of location 12 and the miscellaneous orientations just discussed, are illustrated in Figure 11.

The fracture pattern for the northern belt is representative of structural deformations characteristic of the serpentinite-schist contact (Fig. 11A) whereas that for the southern belt (Fig. 11B) is more representative of the response to deformation of a larger serpentinite pluton. The patterns for both can be explained by direct analogy with normal and contact patterns in the schist and thus can be related to them with a reasonable degree of confidence. The authors interpret the data to illustrate that shear, slip parallel to strike, and oblique joints in serpentinite correspond to the D_1–D_2 and

D_3 deformational patterns noted in the schists, which are in turn based on the undifferentiated S_1–S_2 and the S_3 cleavages in these schists. All of these features can be seen in Figure 11.

The major concentration of poles in the northern belt are nearly vertical, east–west striking fractures oriented at an angle of about 40° to the northeast regional strike. Fractures transverse and parallel to this regional strike are present to a lesser extent. Because of the near parallelism of strike between S_1–S_2 and S_3 most of these maxima cannot be related to a specific deformation, although small maxima do occur at the positions of S_1–S_2 and S_3 schist cleavages, resulting from a difference in dip of the two sets. It seems probable that planes in the serpentinite having the same strike as cleavages in the schist but a steeper dip, are directly analogous to the cleavages in the schist, but are a consequence of the steepening that seems to be a general characteristic at the contact in both schist and serpentinite. All maxima are diffuse with a wide scatter resulting in a nearly complete girdle of steeply dipping to vertical planes which could, in part, reflect rotational movement from shearing. The majority of planes are south-dipping.

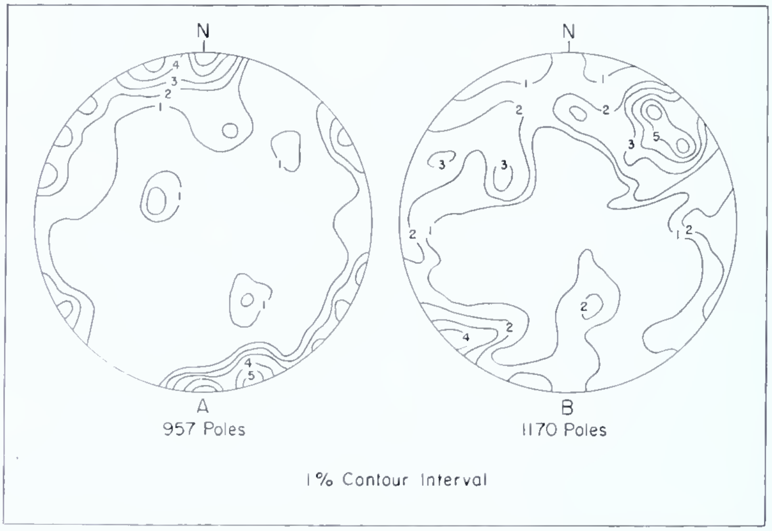


Figure 11. Summary of all fractures in the northern (A) and southern (B) serpentinite belts, excluding location 12

Most of the relationships mentioned for the northern belt also apply to the southern serpentinite (Fig. 11B). Here, however, northwest striking fractures are dominant. These are interpreted to be *ac* (extensional) and are characteristic of this larger serpentinite, in contrast to the predominant oblique shears of t northern serpentinites. Fractures having t S_1–S_2 schist orientation are more pronounc as a consequence of less extensive obliterati by later shearing and less interference fr boundary effects than fractures in the north serpentinites. In both belts, later stresses a pear to have disturbed previously existing fr ture orientations, but not beyond the abil to relate them to the earlier patterns.

EVIDENCE FOR ROTATIONAL MOVEMENT

Rotational movement has been suggeste the discussion of fractures near the sc serpentinite contact. The term "rotati movement" is used here to describe effec shearing which are most pronounced along contact and which appear to diminish a from the contact. As a consequence, pre-e ing planes in both schist and serpentinite to become more nearly aligned parallel to shear direction the closer they are to the tact.

Such a rotation would be expected to duce diffuse concentration maxima and in cases to produce a shift in the position of maxima from their original orientations pecially if the sharing resulted in faulting significant displacement, as for examp location 8 (Fig. 4). Two examples, in adc to those already mentioned, that migh partially explained in this manner are ed in Figure 12. However, the evidence, cially for direction of rotation, is both rect and inconclusive.

ther previously illustrated locations for ch a plausible rotation might be inferred Counterclockwise: Fig. 2, locations 19–23; 3, locations 27, 29, 31; Fig. 4, location 6; ckwise: Fig. 4, location 8; Fig. 12, location Indeterminate: Fig. 4, location 3; Fig. 8, tion 14; Fig. 12, location 28; Fig. 10A, acture cleavage." Axes of rotation for the ter and shifts on each of these diagrams e plotted on a stereographic projection, but consistent pattern resulted, except to note t all of the axes are steep, varying from ut 60° to vertical. On the basis of these a, rotational movement from shearing stress ng the schist-serpentinite contact probably urred.

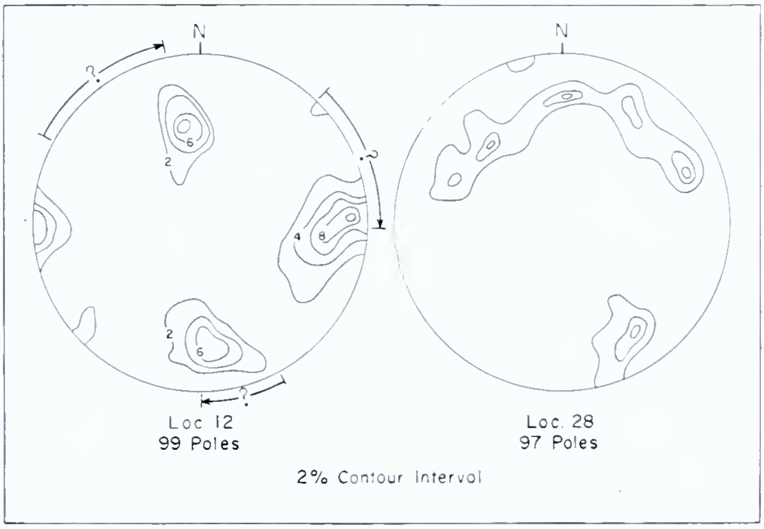


Figure 12. Fractures in serpentinite that suggest rotational movement

SCUSSION OF THE SERPENTINITE FORMATIONAL HISTORY

agenetic Relationships Derived m Structural Considerations

There are several methods by which age ationships that bear upon serpentinite demation may be determined. The methods which data are available are: direct observan of transecting fracture pairs; analogy with redetermined sequence in the surrounding intry rock; observation of, and inference m, relationships at the serpentinite contacts; petrographic analysis; and absolute age determination methods.

The use of fracture pairs in serpentinite to arrive at age relationships is both difficult and uncertain. The normal procedure using offset of bedding or flow layering cannot be applied because these features are absent. As a result, only the offset of one fracture by another can be used, and even here the multiplicity of fractures present renders the task of tracing a particular fracture from one side of a fault plane across to the other difficult. A total of only 34 crosscutting relationships were sufficiently clear to be usable. Nevertheless, even this small a number is unwieldy. The wide scatter of points, the relatively large number of pole maxima, and repeated slippage along pre-existing planes (Table 2, measurements 1, 2, 3, 4) add to the confusion. In spite of this, the pole-pairs measured do fall within areas of maximum pole concentrations of serpentinite fractures, and they are the most direct source of evidence available.

The readings taken are listed in Table 2. They represent measurements from the two New Texas quarries (locs. 5, 7) and from the Cedar Hill quarry (loc. 17). In order to arrive at some method for visualizing this maze of numbers, the following procedure was employed in constructing Figure 13: (1) the data from the two New Texas quarries and from Cedar Hill were considered separately, to reduce the number of planes under consideration at any one time and to see if any differences between the northern and southern serpentinites could be ascertained; (2) each pair of fractures was plotted on a Schmidt net and connected by an arrow pointing to the younger of the pair. The composite of these points fell into most of the typical maxima previously described for serpentinite; (3) from the resulting point concentrations various combinations of age sequences from one group of points to another were tried. The sequence determined as the best fit to the data was that which agreed with the age relationships for the greatest number of points; (4) the group of points representing each sequence was then plotted separately (Fig. 13). The data in Table 2 are keyed to these diagrams by letter in order to better visualize and evaluate this procedure. Certainly this method has no statistical validity. However, it should be emphasized that no attempt was made to arrange these sequences by analogy with the S_1–S_2, S_3 nomenclature. The sequence was determined solely from the relative age relationships of the groups of plotted points (step 3).

The sequence thus arrived at for the northern serpentinite quarries is shown in Figure 13A, with oldest to youngest from left to right. These nets can now be related to the previously used "*S*" surface designations. The two points on net (a) fall in the area of the S_1–S_2 strike-slip poles. This is followed in turn by an east–west shear (b), several groups of undifferentiated maxima that correspond to an extensional *ac* joint, a north–south oblique shear, and late movement along the northeast strike-slip direction (c), and a nearly horizontal deweylite-filled fracture (d). In addition to conforming to the major maxima at these locations (Figs. 9, 11), these points reinforce the suggestion of relatively late shearing movement.

The sequence for the Cedar Hill quarry in the southern serpentinite (Fig. 13B) is similar and may be interpreted as follows: (e): S_1–S_2 cleavage orientation; (f): extensional *ac* joints belonging to the D_1–D_2 deformational pattern; (g): S_3 cleavage orientation; (h): a north–south oblique joint; (i): nearly horizontal deweylite and late movement along pre-existing planes. The sequence is nearly the same as that determined for the northern serpentinite with the addition that poles are present which coincide with an S_3 maximum. However, the exact position of this maximum in the sequence is uncertain since the positioning of diagram (g) before (h) is dependent upon only two points (Table 2).

In summary, this method of presenting a
relationships between transecting fracture pa
is consistent with the "*S*" surface nomenclatu
used in interpreting the previous Schmidt r
diagrams, both the S_1–S_2 and S_3 fractures bei
present in this order. The data also suggest t
the sequence of formation of these fractu
has been first *bc* (or "cleavage"), followed
transverse (extensional) joints, and finally
oblique (shear) planes. Late movement
earlier formed planes seems certain. The t
number of poles in each diagram incre
toward the right, which could be expec
because the youngest deformations will y

TABLE 2. TRANSECTING FRACTURE PAIR MEASUREMENTS*

	New Texas quarries: north serpentinite belt	
	Older	*Younger*
	N. 30° E., 85° SE. (a)†	N. 7° E., Vert. (c)
(1)*	N. 30° E., 85° SE. (a)	N. 87° E., 83° SE. (b
	east-west, Vert. (b)	N. 59° E., 75° NW. (
	east-west, Vert. (b)	N. 2° W., 85° SW. (c
	N. 83° W., Vert. (b)	N. 40° W., Vert. (c)
(2)	N. 86° E., 75° SE. (b)	N. 47° E., Vert. (c)
	N. 5° W., Vert. (c)	N. 13° E., 14° NW. (
	Cedar Hill quarry: south serpentinite belt	
	Older	*Younger*
	N. 44° E., 40° SE. (e)	N. 69° W., 87° NE. (
	N. 51° E., 33° SE. (e)	N. 3° E., 68° NW. (h
	N. 41° E., 34° SE. (e)	N. 62° W., 85° SW. (
(3)	N. 50° E., 55° SE. (e)	N. 15° W., 73° SW. (
	N. 19° W., 76° NE. (f)	N. 25° E., 53° NW. (
	N. 25° W., 86° SW. (f)	N. 17° E., 87° NW. (
	N. 61° W., 70° SW. (f)	N. 32° E., 79° SE. (g
	N. 49° W., 70° NE. (f)	N. 2° E., 80° NW. (h
	N. 50° W., 60° SW. (f)	N. 28° E., 60° NW. (
	N. 50° E., 49° NW. (g)	N. 17° E., 25° SE. (i
	N. 69° E., 73° NW. (g)	N. 15° E., 77° SE. (i
	east-west, 45° N. (g)	N. 30° E., 56° SE. (i
	N. 52° E., 67° NW. (g)	N. 5° W., 80° NE. (i
	N. 48° E., 60° NW. (g)	N. 62° E., 35° SE. (i
	N. 86° W., 30° NE. (g)	N. 40° W., 80° SW. (
	N. 74° E., 25° NW. (g)	N. 23° W., 87° NE. (
	N. 80° W., 77° SW. (g)	N. 3° E., 68° NW. (h
	N. 44° W., 40° NE. (g)	east-west, 39° S. (i)
	N. 24° E., 77° NW. (h)	N. 78° W., 86° NE. (
	N. 20° E., 72° NW. (h)	N. 30° E., 56° SE. (i
	N. 10° E., 73° NW. (h)	N. 80° E., 27° NW. (
	N. 6° W., Vert. (h)	N. 16° E., 17° NW. (
	north-south, 67° W. (h)	N. 14° E., 36° SE. (i
	N. 9° W., 69° SW. (h)	N. 22° E., 27° SE. (i
	N. 9° W., 80° NE. (h)	N. 34° E., 16° SE. (i
	N. 21° W., 75° SW. (h)	N. 24° E., 44° SE. (i
(4)	N. 18° W., 87° SW. (h)	N. 51° E., 26° SE. (i

---

[*] Numbered fractures show evidence of repeated
page (*See* text).

[†] Letters a–i are sequential designations usec
Figure 13.

most easily recognizable age relationships. eatures observed at the serpentinite-schist tact and serpentinite-metagabbro contact provide some clues to the deformational ory of the serpentinite. Chief among these he parallelism of the northern serpentinite h the dominant regional cleavage (S_1–S_2 S_3 have a similar strike) and the deviation n this parallelism by the southern belt ward from the Pennsylvania-Maryland te line. This observation implies that the aller, northern serpentinite has responded to ormational stresses in such a way as to ome conformable with the regional pattern, ereas the larger, southern serpentinite has ained, at least to some degree, an original ntation controlled by some structural ament other than the presently recognized ormations (D_1, D_2, and D_3). A similar ication that serpentinite tended to act as a stant massif to stress is the extremely tight vron F_3 folds of several inches amplitude nd in mica schist immediately next to the tact at location 3 (Pl. 1). Magnetite con- utes up to about 60 per cent in layers allel to the contortions of the folding, gesting that the magnetite (which is post- rusion of the ultramafic pluton) is pre-D_3. her observations, pertaining to contact aring and faulting, have been mentioned. ey are characteristic of the contact and more recent than the time of intrusion of the ultramafic pluton, although intrusion (or emplacement) also may have been accompanied or facilitated by shearing. Similar shearing at ultramafic rock contacts has been described by Kovenko (1949) in Turkey, Bloxam and Allen (1960, p. 2) at South Ayrshire, by Hill (1959, p. 1469–1470) in Las Villas Province, Cuba, by Coleman (1961, p. 210–213) and Bloxam (1960, p. 565, 567) in California, and by Noble and Taylor (1960, p. 193) in a comparison of Alaskan and Siberian ultramafic bodies. From this, it is clear that Alpine-type ultramafic rocks commonly lie along zones of shear, and that at least some of this shearing may be interpreted as younger than emplacement.

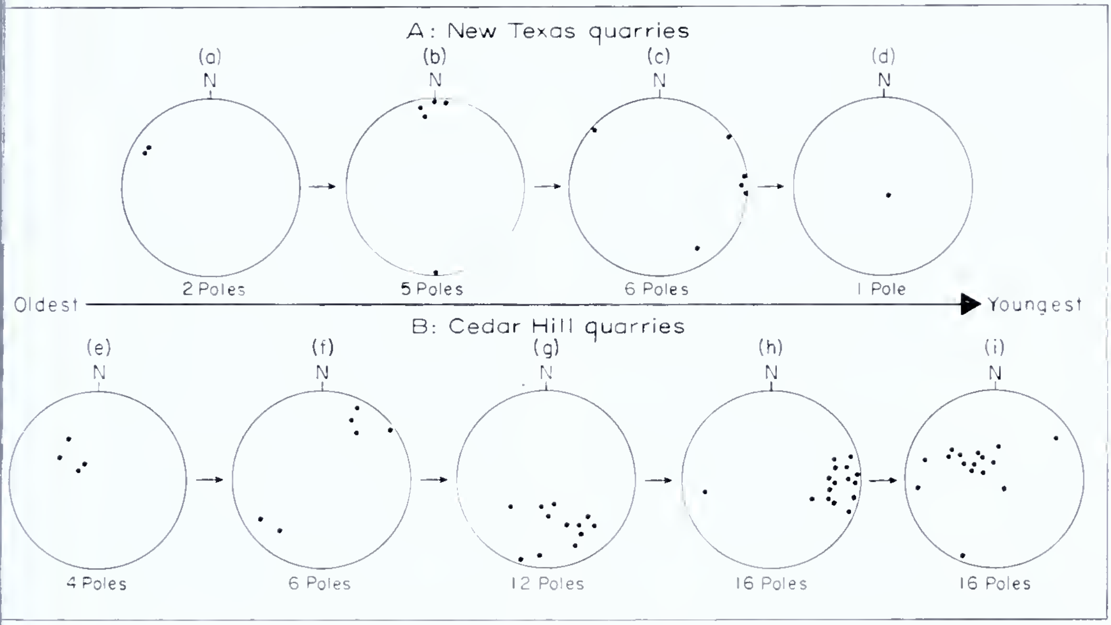


Figure 13. Age relationships indicated by transecting pairs of fractures in serpentinite

To date, approximately 250 serpentinite petrographic sections and 80 contact schist sections have been examined. The conclusions pertaining to rock deformation indicate that:

(1) There were several stages of serpentinization, some of which are separated by significant deformational stresses.

(2) Initial serpentinization of olivine fills fractures with an S_1–S_2 orientation at Cedar Hill and must have occurred during late D_1 or during D_2. In the northern serpentinite, minor granulation occasionally separates olivine and initial serpentine from the later, major serpentinization.

(3) The northeast striking gash fractures now containing chrysotile (Fig. 10C) are younger than this major serpentinization and younger than antigorite veinlets with the same orientation, but older than a period of shearing. At present, these data have largely been obtained from the northern serpentinite, but can be expected to hold true for both belts.

As mentioned previously age determinations on micas and feldspar have revealed two periods of metamorphism in this region (450–550 m.y. and 300–350 m.y.) (Tilton and others, 1958; Tilton and Davis, 1959; Kulp and Ecklemann, 1961; Stern and Rose, 1961) as well as a third in Georgia at about 250 m.y. by Kulp and Ecklemann (1961). Because D_3 evidences no recrystallization along the associated S_3 cleavage, it is probably younger that the 300–350 m.y. date. This leaves two deformations (D_I and D_2) and two ages of regional metamorphism (350 and 450 + m.y.) which may or may not be correlative.

Stress-Yield Characteristics of Serpentinite and Schist

The differences noted in the fracture patterns of serpentinite and schist are indicative of the difference in the character of their response to the same regional stresses. The large number of pole maxima in serpentinite correlative with patterns recognized in the country rock is significant. It was noted earlier that the less competent mica schists exhibited S_3 cleavage whereas only in the more competent quartzitic schists was the S_I–S_2 cleavage noticeably preserved; yet, "S" orientations for each appear in serpentinite. Furthermore, the number of large scale fracture surfaces (*i.e.*, excluding "cleavage") per unit area is much greater in serpentinite than in schist, even away from the highly sheared contact. Since one might expect serpentine to be more plastic than the surrounding country rock, some explanation should be offered to explain this "brittle" fracturing and the preservation of earlier deformational patterns.

The schists, considered locally, are nonhomogeneous in that they are composed of units such as quartzites, metagraywackes, mica schists, and metavolcanics, which all have different flow characteristics and which would not be expected to reach the rupture point at the same time under the same regional stress. They are also anisotropic because of strongly developed planar elements such as bedding, mineral orientation, and well-developed cle age inherited from an earlier deformation. of these elements will act as effective slipp planes under a later deformation.

The serpentinites, on the other hand, relatively homogeneous, with the occasio exception of massive chromite lenses near north contact of the southern serpentin They should also be relatively isotropic si the only banding present is weakly develo and would not be expected to act as a ma plane of weakness.

With the above characteristics in mind, assuming a homogeneous regional stress fi (either D_I, D_2, or D_3), this stress field will homogeneously distributed with respect to schists because their large areal extent enal them to be considered as a single unit. H ever, the local anisotropism provides plane easiest adjustment to stress application s that the stress components will tend to aligned parallel to these planes, *e.g.*, beddi *etc.* The situation is somewhat different w respect to the serpentinites where the regic stress field will be essentially nonhomogene because of the following factors, which cre locally variable stress vectors: (1) the irregu ities of shape and the small volume of serpentinites, when contrasted with the ext of the schists, will create variable bound stresses; (2) the southern serpentinite str at an angle to the regional schists, and since recognized deformations are superimpo upon this divergent pattern, local variati in stress will also result; (3) locally, chromite lenses will act as resistant mas and, (4) local variations in the degree serpentinization which are especially notice at the contact will locally distort and perh facilitate the transmission of the regional st field. As a result of these irregularities, serpentinites will exhibit local deviations w a consequent scatter of pole maxima. Howe they also are more responsive to the tr mission of the variability of the stress f because they do not have the planes of ferred orientation that are present in schists and that tend to align the stress c ponents parallel to them. As a conseque shear, transverse, and *bc* joints would expected in serpentinite to a greater ex than in the schists because of a lack of prefe planes, but with greater scatter of their max because of local stress variations, especi contact shearing.

Other factors which may have played

ortant role in the serpentinite defor- ional pattern but which are difficult to uate are the duration of the regional stress l, and the possibility of reintrusion of the entinite. For example, if the stress were that it rapidly exceeded the yield point of entine, then there would be little flow a maximum of "brittle" fracturing. How- , at least D_1–D_2 shows evidence of flowage recrystallization in the schists so that this onal stress probably did not accrue rapidly. he serpentinite was reintruded to its present of emplacement after an initial crystalliza- at depth, this either occurred pre-D_2, e the D_1–D_2 pattern is superimposed, or hout greatly disturbing the earlier orienta- s. The former seems more plausible.

mary of Serpentinite Deformational History

here is no evidence that the regional rmations responsible for the major struc- s in the area have squeezed the serpentin- "like toothpaste" after they were once laced; only the fragmented character of northern serpentinites suggests such a mode ntrusion, and this was apparently previous the undifferentiated D_1–D_2. On the trary, the great variety and complexity of ittle" fracturing was caused, at least in part, a nonhomogeneous stress field (*i.e.*, non- ogeneous with respect to the serpentinites) ng upon a relatively homogeneous and ropic rock unit. This interpretation is patible with either intrusion or reintrusion vious to the establishment of the D_2 frac- patterns. Shearing seems to have been re characteristic of a younger deformational ss with only minor yield by flow that de- ned and reoriented earlier planes, especially he schist-serpentinite contact which acted dominant plane of weakness. The ultra- ic pluton itself acted as a resistant buttress the various regional stresses, retaining an ier strike orientation at a small angle to the onal strike and resulting in the warping and ting of schist fold axes and cleavage within w hundred feet of the contact.

ased upon this reasoning, a sequence for deformational history of the serpentinites be proposed. However, at each step rnatives are possible, and this sequence is ely the one that seems most reasonable to authors.

he initial emplacement of ultramafic terial seems to have been controlled by a ctural lineament other than one within the deformational systems presently recognized. Such a lineament might well be the Appalachian geosyncline and/or basement configuration as proposed by Hess (1955) who recognized two belts, one on either side of deformed mountain systems. Using this terminology, both the "northern" and "southern" serpentinites of Pennsylvania and Maryland belong to Hess' western ultramafic belt. Or the locus of intrusion may have been controlled by a major basement fault system, possibly coinciding with the offshore wrench fault noted by Drake (1963) at about lat. N. 40° (but tentatively located in the Triassic to the north by Woodward, 1963, p. 293–300). Since the deformational patterns for D_1 and D_2 could not be separated in this study nor in the work of Freedman and others (1964) in the serpentinite area, this original emplacement could have occurred either during D_1 or very early in D_2. The same statement applies to any reintrusion mechanism. Initial serpentinization of olivine, which is quantitatively a minor part of the total serpentinization, was followed in some cases by crushing and granulation. This could be interpreted as the effects of reintrusion contemporaneous with the later and major period of serpentinization. Contact metasomatism occurred, coincident with or slightly later than the emplacement of the serpentinite into its present position.

During D_1–D_2 deformation, *bc* fracturing (S_1–S_2) was dominant within the serpentinites, forming the majority of fractures observed, the chrysotile veins, reserpentinizing the ultramafic mass along the contacts which destroyed all pre-existing ultramafic textures, and realigning the cleavage in the schist adjacent to the serpentinites. This was followed by transverse fractures that were filled with cross-fiber chrysotile. The final event of importance appears to have been shearing, which was especially pronounced along the contacts, with minor flow of serpentine and probably additional reserpentinization along the contacts. Since pre-existing planes have been rotated and reoriented, presumably, but not necessarily, this event belongs to the last recognized stage of deformation, D_3. The position of steatitization and pegmatitization in this sequence are uncertain except to say that they postdate the major stage of serpentinization.

CONCLUSIONS

From a consideration of the distribution of fracture surfaces and lineations for 32 stations in schist and serpentinite in southern Lancaster County, comprising approximately 4000 measurements, deformational patterns emerge which are consistent and which conform with other recent investigations. In the typical schists away from intrusive contacts, three cleavages have been recognized north of the serpentinites, two of which can be separated in this area (S_1–S_2 and S_3) and which can be traced throughout the center of the southern serpentinite and locally near the contacts of the northern serpentinite bodies where contact shearing has not obscured earlier orientations. Both transverse and oblique fractures are present which can be interpreted in terms of these *S*-surfaces, the latter becoming dominant in both rock types only near the schist-serpentinite contact. The three *S*-surfaces are interpreted to imply three deformations, although only two (D_1–D_2 and D_3) can be differentiated here. This sequence of deformational patterns has been observed and inferred from several perspectives: from cleavage relationships in the schist; by comparison and analogy between schist and serpentinite fracture surface pole plot maxima; by offset relationships from transecting fracture pairs in serpentinite; and by correlation with petrographic observations. The more recent deformations seem to be noticeably characterized by shearing, although it may be that this shearing has merely obliterated or coincided with earlier shear orientations.

The presence of these patterns in both schist and serpentinite indicates that the same deformations have affected both, and therefore the most recent deformation during which the serpentinites could have been emplaced is early in the D_2 disturbance. They also indicate certain differences in response to deformation between schist and serpentinite: (1) the more competent, quartz-rich schists tend to preserve the earlier deformational patterns; (2) transverse jointing is probably more characteristic of schist whereas oblique shear joints are more common in serpentinite, at least near the contact; (3) there is a greater variety in orientation, a more complex fracture pattern, and a greater quantity of fractures in the serpentinites than in the schists; and (4) within the serpentinites, the smaller the mass the less competent its response, the more nearly it conforms to the regional schist strike, and the more likely it is to have yielded by intense shearing. In general, the serpentinites have responded to stress by relatively brittle fracturing rather than by flow. As a consequence of these data and the observation t
the schists are relatively inhomogeneous a
anisotropic whereas the serpentinites
relatively homogeneous and isotropic, t
authors suggest that the serpentinites me
directly reflect small variations in the str
field; that is, where possible, the schists ha
tended to yield along pre-existing planes, su
as bedding and schistosity, which are n
present in the serpentinite.

Deformation at the schist-serpentinite c
tact is characterized by: (1) shear joints; (2
steepening of the transverse and strike-s
surfaces; (3) a general parallelism betwe
cleavage in the schist and the serpentin
contact (although this is not always the case
a regional basis); (4) a predominance wit
the serpentinite of southward dipping plan
(5) faulting or shearing; (6) reserpentinizati
and (7) metasomatic alteration. All these ha
been controlled to a large extent by a ma
structural discontinuity and by the subsurf
attitude of the southerly dipping serpentini
In turn, this attitude of the serpentinite see
to have been controlled not by presen
recognizable deformations but by some earl
structural lineament such as geosynclinal
basement configurations that were modified
succeeding regional metamorphic phases. Th
relationships should become much clea
when the metaigneous and metasediment
units to the south of the serpentinites have be
carefully studied.

Certain minerals exhibit preferred orien
tions. Cross-fiber chrysotile veinlets are p
dominantly parallel to the regional strike a
less commonly perpendicular to it. Intrus
chlorite-vermiculite (–feldspar?) pegmati
are generally steep and south-dipping. S
ondary deweylite is largely confined to gen
dipping fractures with no particular directio
orientation. Banded, disseminated chrom
and some magnetite parallel the north cont
of the southern serpentinite and therefore m
be primary in origin.

As a general statement, it is obvious t
structures within serpentinized Alpine ult
mafic plutons are complex and that th
interpretation is therefore not only compl
but also somewhat ambiguous. However, o
a knowledge of structures in the surround
country rock has begun to emerge, the m
diverse and less easily identifiable structure
serpentinites can be deduced with the assura
that some of the interpretations stand a h
probability of being correct.

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ort Notes

IS M. LAPHAM
LIAM A. BASSETT

AR DATING OF ROCKS AND TECTONIC EVENTS IN THE DMONT OF SOUTHEASTERN PENNSYLVANIA

tract: Structural and petrographic data and r determinations on muscovite, biotite, ortho- , and whole-rock samples in the Piedmont ince of southeastern Pennsylvania show that: mafic intrusion and contact metamorphism place at least 460 m.y. (million years) ago; ite in small mafic intrusions at the ultramafic contacts is 460 m.y. old; apparent thrust slices he Martic Line are older than 330 m.y.; a onal metamorphism occurred approximately 330 m.y. ago and is tentatively correlated with the second of three recognized deformations; and granitization of Peters Creek Schist in the vicinity of the ultramafic pluton occurred 330 m.y. ago or later. Ages between 460 m.y. and 330 m.y. and ages younger than 330 m.y. are believed to be anomalous because of argon leakage resulting from greenschist-facies metamorphism, cataclasis of muscovite, and incomplete recrystallization of muscovite in granitized gneiss and pegmatite.

oduction

umerous age determinations for the Appa- ian Piedmont province have been reported summarized (Tilton and others, 1958; on and Davis, 1959; Stern and Rose, 1961; p and Eckelmann, 1961; 1962; Hadley, 4). In general, the dates fall into five groups, ough there is considerable scatter. Zircon microcline have yielded two Precambrian s, 1000–1150 m.y. and 800–900 m.y., and wer Paleozoic group from 450–550 m.y. determinations by the K-Ar method on tite and muscovite have yielded three nger groups at 300–350 m.y., 230–290 m.y., 180–190 m.y. The Paleozoic ages probably lt from metamorphic recrystallization of r units such as the Baltimore Gneiss, the t Deposit "granodiorite," and the Glenarm ies of metasedimentary rocks.

hniques

riented samples were collected where ctural patterns (*S*-surfaces) have been sured and where considerable field mapping laboratory work have been conducted pham and McKague, 1964; Lapham, unpub.). Thin sections and X-ray diffractometer terns of all the dated samples were analyzed determine extent of alteration, evidence of a recrystallization, and paragenesis among the micas. Additional metamorphic units, which were not dated, were studied petrographically to clarify the deformational history.

A portion of the sample to be dated was crushed and sieved between 0.149 mm and 0.177 mm. Whole-rock dates for which micas were not separated are noted in Table 1. Coarsely crystalline muscovite was hand separated. The remaining portion of the sample was used for X-ray and petrographic analysis.

Potassium analyses were made on dissolved samples by X-ray spectrometry employing the technique of standard addition. Argon determinations were made by isotope dilution on a mass spectrometer. A description of the techniques may be found in Bassett and others (1963). The mean deviation for the age determinations is 5 per cent. All the dated samples except at location 13 were run at least twice.

Descriptions

The stratigraphic units in the asymmetric Peach Bottom syncline of Pennsylvania are the Peach Bottom Slate in the center, the Peters Creek and Wissahickon formations on the flanks (Fig. 1). The last two formations are complex metasedimentary rocks, but are dominantly either a nearly pure quartzite or a quartz-poor mica schist. Bodies of serpentinite intrude the Peters Creek on the southeast flank of the syncline. North of the serpentinites the

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logical Society of America Bulletin, v. 75, p. 661–668, 3 figs., July 1964

rocks have a relatively uniform grain size and show no sericitization.

The Peters Creek between the serpentinite bodies, however, contains xenoblastic mica and quartz with chlorite, stilpnomelane, or biotite reaction rims. Fine-grained muscovite (Fig. 2, sericite alteration) has replaced coarse muscovite, quartz, plagioclase, and potassium feldspar. Partly assimilated inclusions of pelitic schist with xenoblastic mica and quartzite inclusions are common. The rock foliation has been destroyed so that the unit resembles a fine-grained granite and hence is referred to as granitized Peters Creek.

The serpentinites are altered dunites or harzburgites and consequently contain no minerals suitable for K-Ar dating. Howeve
there are small lenses of igneous and hydr
thermally metasomatized rocks that are loc
ized along the ultramafic rock-schist conta
and are believed to be younger than t
ultramafic rocks. One of these (at location
on Figure 1) contains quartz, bimodal musc
vite, albite (probably in part recrystallize
and epidote and is transitional between plag
clase hornblendite and quartz-mica schist.
is probably metasomatic in origin. The pegm
tite at location 13 on Figure 1, however, co
tains orthoclase, quartz, and tourmaline a
is probably magmatic in origin.

Recent work in the Pennsylvania Piedmo
(McKinstry, 1961; Freedman and others, 19(

TABLE 1. K-AR AGE CORRELATIONS, LANCASTER COUNTY, PENNSYLVANIA

Location (See Fig. 1)	"*S*" surfaces present	K-Ar age in m.y. ± 5 per cent	Avg. mica size, mm	Alteration	Unit
1	S_1, S_2		0.160 (M)	C:slight	Wissahickon metagraywacke
2	S_1, S_2	360 (B) (M)	0.380 (B) 0.100 (M)	C:extensive Se, G:moderate	Wissahickon metagraywacke
3		285 (O)			Pegmatite
4	S_1, S_2		0.210 (M)	C: slight-moderate	Wissahickon Schis
5	S_1, S_2		0.090 (M)	C:extensive	Wissahickon metagraywacke
6	S_1, S_2	325 WR	0.065 (M)	C:extensive	Peters Creek Schis
7	S_1, S_2	330 WR	0.090 (M)	C:extensive	Peters Creek metagraywacke
8	S_1, S_2	305 WR	0.025 (M)	C:extensive	Peters Creek quartzitic schist
9	S_1, S_2	320 WR	<0.04 (M)	C:extensive	Peach Bottom Sla
10	$S_{1\text{-}2}$		0.040 (M)	C:extensive	Peters Creek quartzitic schist
11	$S_{1\text{-}2}$		0.400 (M) 0.070 (M)	C, Se:extensive	Peters Creek quartzitic schist
12	$S_{1\text{-}2}$. S_3		0.460 (M) 0.035 (M)	C,Se:moderate	Peters Creek quartzitic schist
13		330 (M)	2.00 (M)	nil	Pegmatite
14		355 50 per cent M, 50 per cent B	0.520 (M), (B) 0.020 (M)	C:moderate Se:extensive	Peters Creek granitized
15		360 (M)	0.600 (M) 0.200 (?)*, (M) 0.020 (M)	C,Se:moderate C,Se:moderate	Peters Creek granitized
16		395 (M)	0.400 (M) 0.020 (M)	Se:extensive	Metasomatized pegmatite
16		460 (B)	0.550 (B) 0.050 (B)	C,Se:slight	Plagioclase hornblendite
17		330 (B)	approx. 0.06 (B)	C:moderate	Port Deposit "granodiorite"

* Possibly trimodal muscovite sizes.

Key: M = Muscovite; B = Biotite; O = Orthoclase; C = Chlorite; Se = Sericite; G = Garnet; WR = Whole-ro analysis.

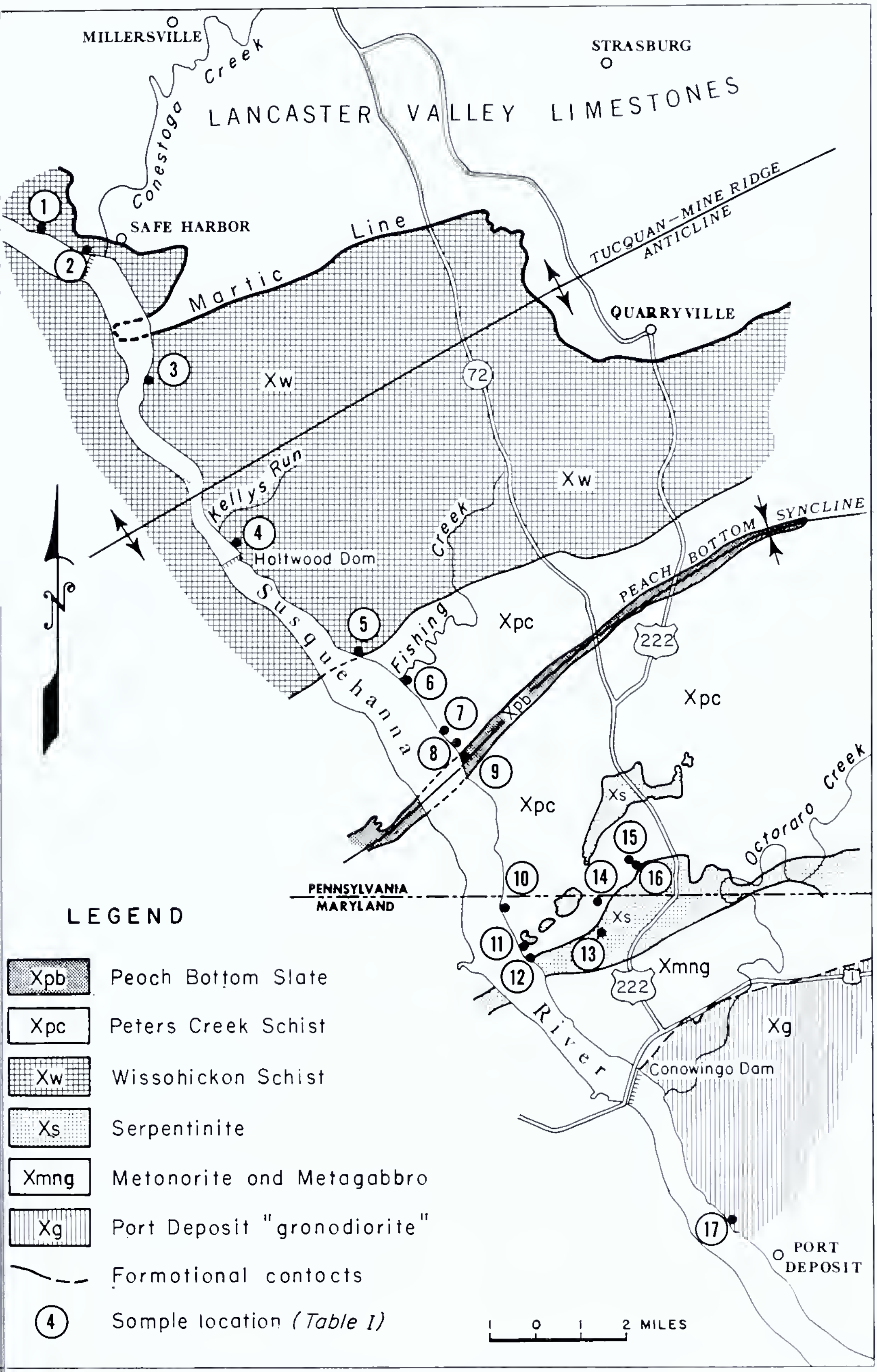


Figure 1. Geologic map of K-Ar sample locations

Lapham and McKague, 1964) has revealed at least three cleavage sequences (S_1, S_2, and S_3), representing three deformations (D_1, D_2, and D_3) that may or may not be widely separated in time. These patterns are superimposed on the limestones north of the apparent thrust slices at the Martic Line and on the schists and serpentinites to the south, and therefore they are younger than these rock types. The first two cleavages (S_1 and S_2) are of regional extent within the Glenarm Series, and the third is found only in the extreme southern part of Lancaster County, Pennsylvania, and northern Maryland. Each of the transecting cleavages is associated with a particular style of deformation, changing in character from intense deformation with considerable flowage and recrystallization during D_1, to folding, broad warping, some recrystallization, and shearing during D_2, to dominantly shearing during D_3 in the southern part of the area. In the area of the serpentinites D_1 and D_2 cannot be differentiated, although to the north they are clearly separable.

Discussion of Data

Introduction. The results of the K-Ar age determinations are tabulated and correlated with structural and petrographic data in Table 1. Numbered sample locations (Fig. 1) are listed from north to south. The age determinations were performed on muscovite, biotite, orthoclase feldspar, and whole-rock samples. The feldspar date (from location 3) is probably low as a result of argon leakage.

Regional metamorphism. Dating by the K-Ar method reveals only the last mica thermal alteration which does not necessarily coincide with the most recent metamorphism. Argon leakage, and therefore apparent young dates, may result from low-grade thermal alteration, mineral replacement, or cataclasis. This is probably the case with several of the dates reported here. However, there is good agreement for the ages of monomodal muscovite (locations 6–9), muscovite pegmatite (location 13), and biotite from the Port Deposit "granodiorite" (at least in part a metamorphic unit: Hopson, 1960). It is noteworthy that although there is considerable variation in extent of alteration and extensive cataclasis of the micas, the resultant ages are relatively uniform, not varying more than about 40 m.y. (Table 1). The range, excluding the lower of the two orthoclase dates and the granitized rocks, is from 290 to 330 m.y. Because the oldest date is most apt to approach the true date of u altered mica, 330 m.y. (plus or minus 5 p cent) is taken as the date of the last maj thermal event.

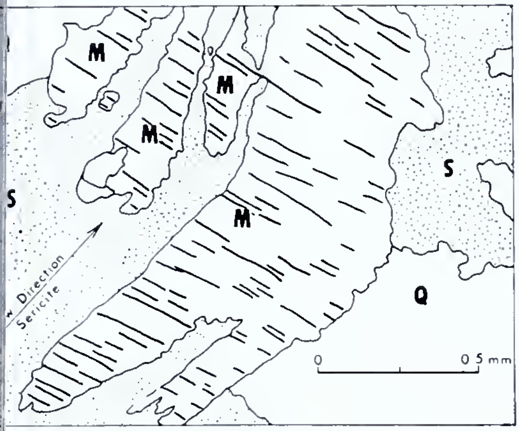
The biotite age (average of three) from t sample of Wissahickon Schist at location 2 somewhat greater than regional muscovite ag This biotite is considerably coarser than t regional muscovite (Table 1) and is replac by fine muscovite, garnet, and chlorite. T sample contains about 35 per cent young muscovite. The age may be the result of alte tion and/or of admixed muscovite and probal represents an older date that has been lower Similarly, other biotite ages, with the excepti of the Port Deposit "granodiorite," are a older than muscovite dates, and older pa genetically than the muscovites with whi they are associated (locations 14, 16).

Correlation of age dates and structural formations. The dates of the regionally me morphosed units and corresponding "*S*" s faces are listed in Table 1. Chlorite crystalli tion and mica reorientation are associated w D_3. This alteration, although not sufficient cause a uniformly younger age, may be sponsible for some of the dates younger th 330 m.y. Consequently, D_1 or D_2 is believ to correlate with the 330-m.y. age.

In thin section two sequences of muscov crystallization can be recognized approximat parallel to the *ac* plane of the F_{1-2} folds. T may indicate that the earlier muscovite oriented by buckling. Both micas may belo to either one or both of the deformations. T authors suggest that the 330-m.y. dated mi may have crystallized during D_2 rather th D_1 for the following reasons: Since mica compositional bands is metamorphic and ear than the two micas in the *ac* plane of the F folds, compositionally, banded mica could a D_1 mica; D_1 could correlate with the kno Taconic disturbance and D_2 with the 330-m event; D_2 (Freedman and others, 1964) essentially an upwarping type of deformat and is consistent with the formation of mi from a buckling-type stress.

A D_2 fold pattern extends northward ac the Martic Line and continues into the fo of the Pennsylvanian Coal Measures which younger than 330 m.y. However, a northw extension of D_2 would not necessarily elimin a D_2 of 330 m.y. (pre-Pennsylvanian) in Piedmont to the south. Deformation may have begun early in the Mississippian continued, progressing northward, into Pe nian or Permian time. Alternatively, use the Coal Measures are relatively less petent than the already deformed schists quartzites to the south, deformation in outh may not have affected the micas of Piedmont. Structural and age determina- work needs to be continued before these tions can be answered more definitely.

ltramafic intrusion. Small lenses of igneous hydrothermally metasomatized rocks local- along the ultramafic rock-schist contact believed to be younger than the ultramafic (location 16). One of the two units at tion 16, a plagioclase hornblendite, contains se crystals of early biotite and fine-grained, biotite with minor fine-grained muscovite. ause the fine biotite and muscovite are finer the collecting sieve used for separation μ), the age of 455–465 m.y. represents the tallization of the older, coarse-grained ite. The rock is extremely dense and appears to have been affected by later, regional amorphism(s). This date (Late Ordovician) represents a minimal age for ultramafic usion.



re 2. Fine-grained muscovite (S) replacing noblastic crystal of muscovite (M) and quartz) in granitized gneiss; traced from photo- icrograph

luscovite from a granitized pegmatite, the r unit at location 16, probably is cogenetic plagioclase hornblendite, although the Ar determination yields an age of 395 m.y. d mapping suggests that it is transitional veen granitized Peters Creek gneiss and ioclase hornblendite. If this is the case, rmal argon loss may be responsible for the rmediate age.

ranitized Peters Creek gneiss. The 350–365-m.y. dates for the granitized Peters Creek samples (locations 14, 15) are somewhat older than the 330-m.y. date for regional metamorphism. At locations 14 and 15, between the two serpentinite belts (Fig. 1) in the southwestern part of the area, the mica sizes are bimodal. Mica grain sizes from other localities to the north (Table 1) are quite distinct (Fig. 2). Typical mica size ranges are illustrated graphically by the histograms in Figure 3. Early, coarse muscovite occurs along the entire strike length of the schist-serpentinite contact suggesting that it is a contact thermal effect from ultramafic intrusion or serpentinization. The coarse muscovite is partially to wholly replaced by fine-grained muscovite (sericite) only where the two serpentinites converge. This sericitization is the major visible characteristic of a granitization that has destroyed pre-existing metamorphic foliation (Fig. 2). As a consequence, the two micas are considerably different in origin and were expected to yield different K-Ar ages. The only coarse mica found north of the serpentinites was a biotite which also is older than 330 m.y. (location 2).

The coarse muscovite content of the granitized rocks ranges from 50 per cent to 90 per cent. Because the minimum sieve size used to collect mica was 0.149 mm (149μ), and because not more than 10 to 15 per cent of the fine-grained muscovite exceeds this size, the reported age date for these rocks was determined largely on the early coarse-grained mica. Thus, a mixed age of approximately 330 m.y. for the fine muscovite and an original age of approximately 460 m.y. for the coarse mica results in the composite ages of 355–360 m.y.

Conclusions

Interpretation of K-Ar dated samples correlated with tectonic events in the Piedmont province of Pennsylvania suggests that: (1) ultramafic intrusion occurred at, or prior to, 460 m.y., probably during Taconic time and resulted in contact metamorphic growth of muscovite; (2) intrusion of plagioclase hornblendite along the schist-serpentinite contact occurred 460 m.y. ago; (3) apparent thrust slices at the Martic Line between limestone to the north and schist to the south are older than 330 m.y.; (4) regional metamorphism at approximately 330 m.y. in the early Carboniferous is correlative either with the first or second regional deformation; and (5) granitization of the Peters Creek Schist, which is spatially associated with serpentinized ultramafic rocks, occurred some time after ultramafic intrusion and after or coincident with regional metamorphism at 330 m.y.

The K-Ar age dates from the Piedmont of Pennsylvania are explained in the light of a series of complex geologic events. In a sense, all dates between approximately 330 m.y. and 460 m.y. are fictitious; that is, they do not represent a metamorphic or structural event. Although many processes contribute to these ages, the most significant in terms of argon degassing is a relatively young granitization in which earlier contact metamorphic micas have been sericitized. Other processes such as successive tectonic deformations with coincident shearing, chloritization, and mica recrystallization have very nearly obliterated 450–465-m.y. mica dates, and probably have lowered 330-m.y. metamorphic mica by 30 or 40 m.y. A 460-m.y. metastable biotite remained within the high rank plagioclase hornblendite despite three succeeding deformations of a lower rank (greenschist facies) because of the extreme competency of the rock. Similar inequalities in extent both of deformation and mineral recrystallization have been observed between adjacent quartzite (competent) and mica schist (incompetent) units. Thus, scatter in ages c tained from the Appalachian Piedmont m very well be a result of increased argon diffusi through less competent rock units even thou both were subjected to a uniform regio stress.

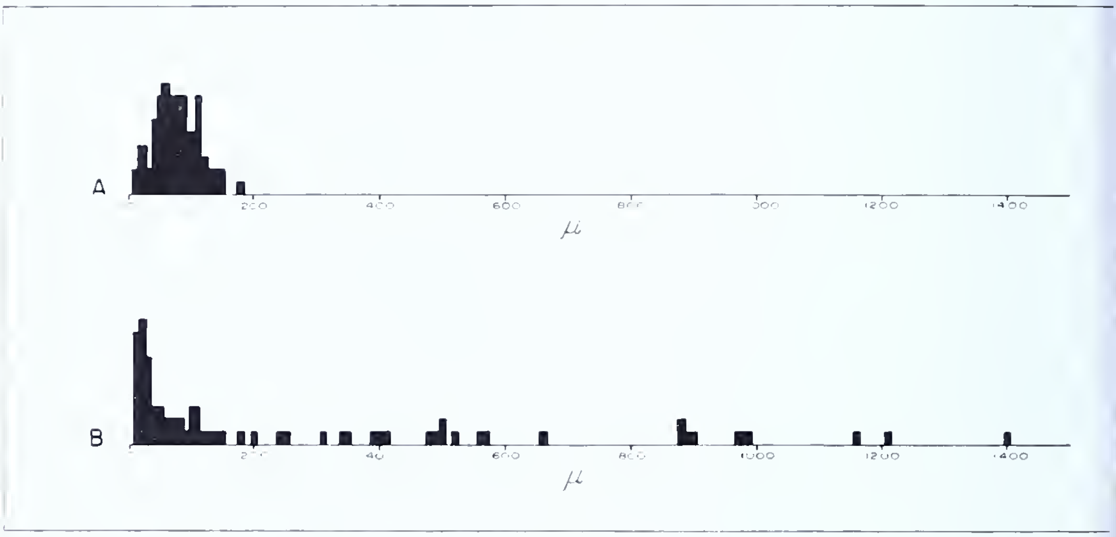


Figure 3. Muscovite size distribution in a typical metasedimentary rock (A) north of serpentinit and a typical granitized gneiss (B) between serpentinites (Fig. 1)

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NSYLVANIA GEOLOGICAL SURVEY, HARRISBURG, PA.; GEOLOGY DEPT., UNIVERSITY OF ROCHESTER, ROCHESTER, N. Y.

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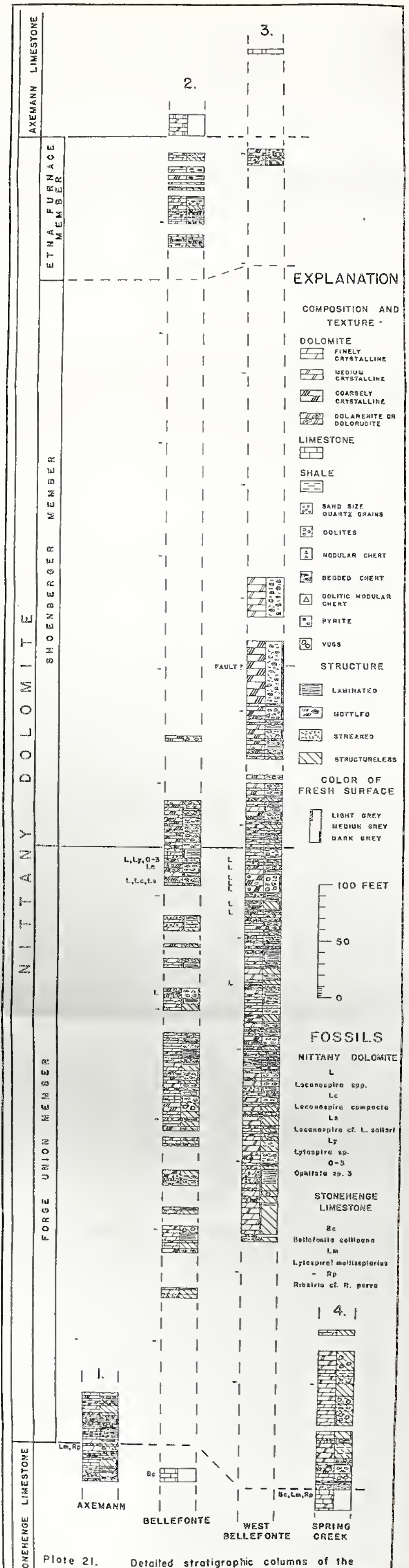


Plate 21. Detailed stratigraphic columns of the Nittany Dolomite for geologic sections measured at and in the vicinity of Bellefonte, Pennsylvania.

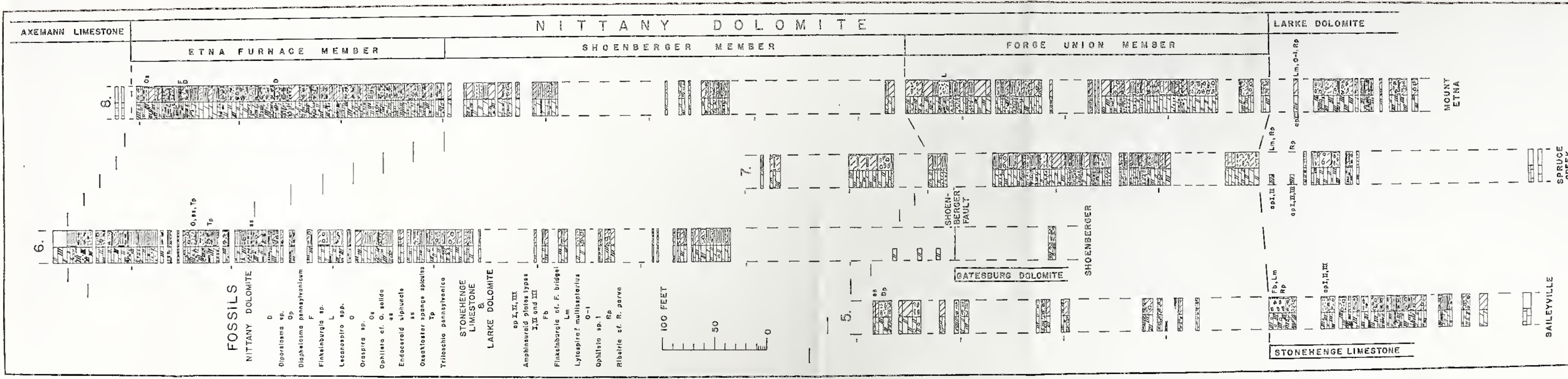


Plate 22. Detailed stratigraphic columns of the Nittany Dolomite for geologic sections measured near Baileyville, Shoenberger, Spruce Creek, and Mount Etna, Pennsylvania.

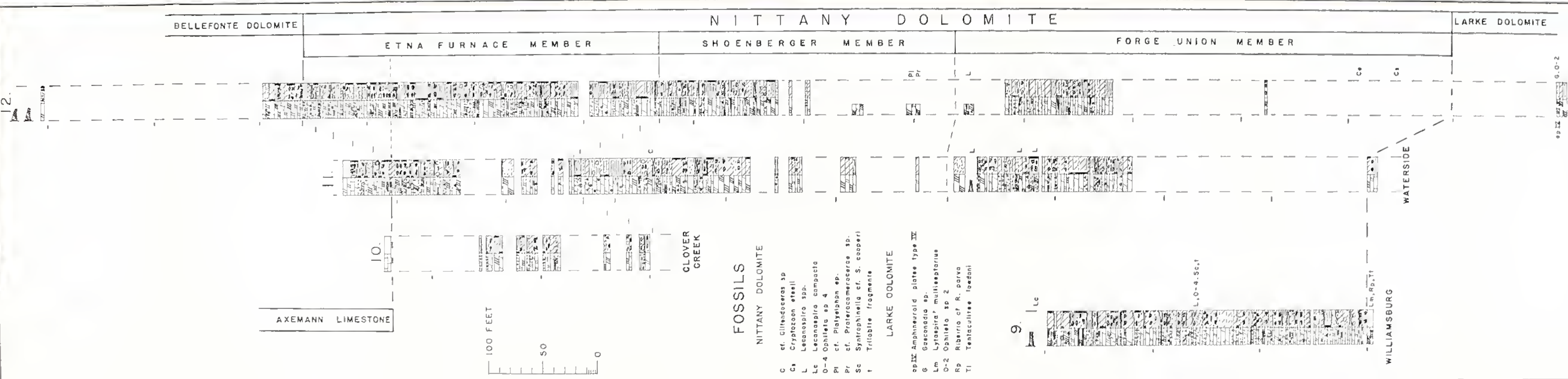
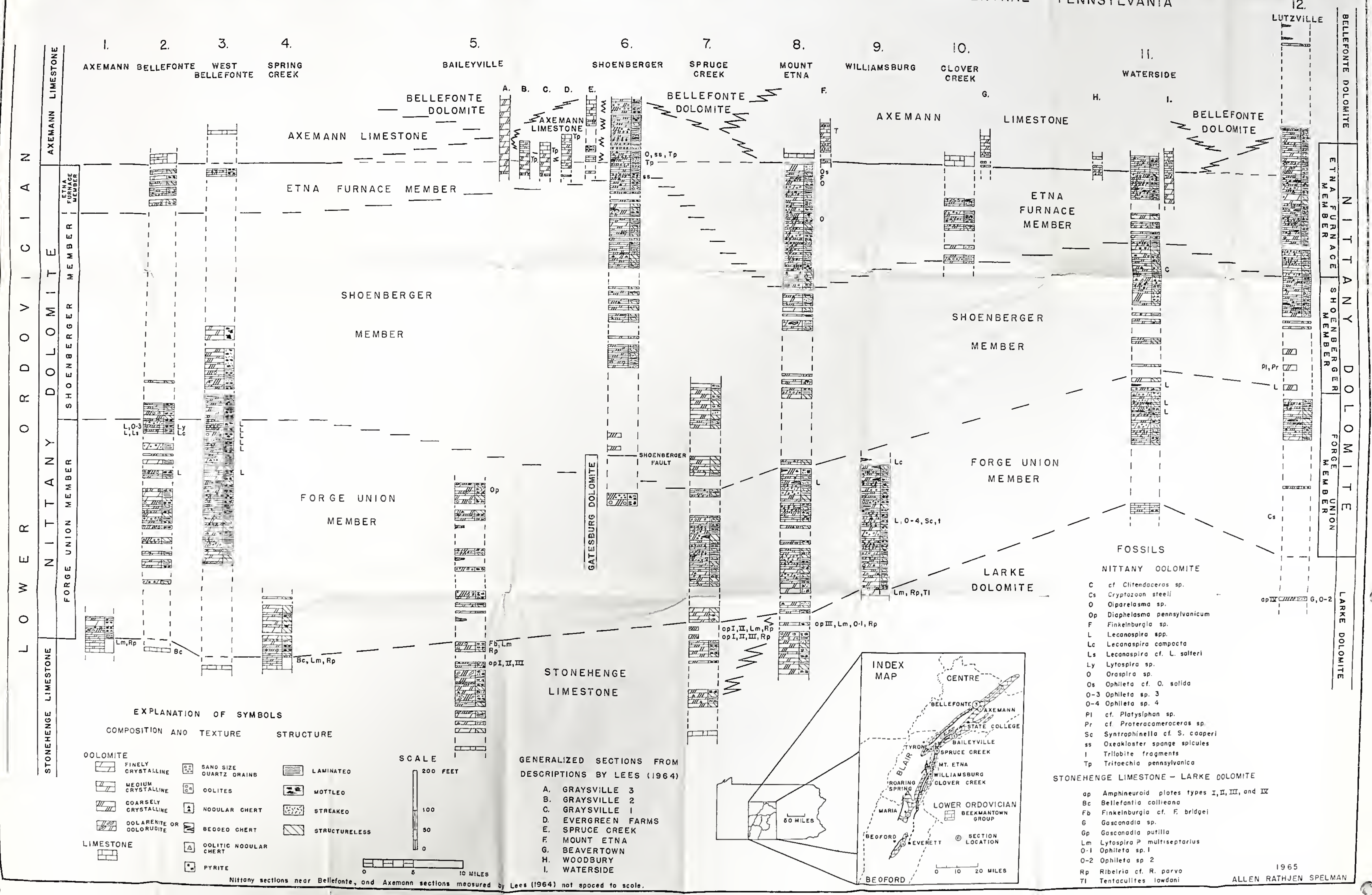


Plate 23 Detailed stratigraphic columns of the Nittany Dolomite for geologic sections measured near Williamsburg, Clover Creek, Waterside, and Lutzville, Pennsylvania

PLATE 24. GENERALIZED STRATIGRAPHIC CROSS SECTION OF THE NITTANY DOLOMITE IN CENTRAL PENNSYLVANIA



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